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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Heat Transfer and Fluid Flow, contains nine modules: Basic Properties of Fluids, Fluid Statics, Fluid Dynamics, Heat Transfer by Conduction, Heat Transfer by Convection, Heat Transfer by Radiation, Change of Phase-Boiling, Burnout and Flow Instability, and Reactor Heat Transfer Limits. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guide are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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ED192089

Nuclear Technology Series

COURSE 4

HEAT TRANSFER

AND

FLUID FLOW

TECHNICAL EDUCATION RESEARCH CENTER - SW

4201 LAKE SHORE DRIVE - SUITE 111

WACO, TEXAS 76710

CE 026 647

U.S. DEPARTMENT OF HEALTH EDUCATION & WELFARE NATIONAL INSTITUTE OF EDUCATION

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P R E F A C E

ABOUT NUCLEAR TECHNOLOGY MODULES

The modules - developed by TERC-SW for use in two-year postsecondary technical institutions to prepare technicians for employment - are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.

Module Prerequisites, which identify the material a student should be familiar with before studying the module.

Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.

Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.

Exercises, which provide practical problems to which the student can apply this new knowledge.

Materials, which identify the equipment required to complete the laboratory procedure.

Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.

Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.

Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.

Test, which measures the student's achievement of the prestated objectives.

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The Nuclear Technology Series will consist of five curricula when completed:

- Nuclear Reactor (Plant) Operator Trainee.
- Radiation Protection Technician.
- Nuclear Materials Processing Technician.
- Nuclear Quality-Assurance/Quality-Control Technician.
- Nuclear Instrumentation and Control Technician.

The completed Nuclear Reactor (Plant) Operator Trainee curriculum consists of the following sixteen technical specialty courses made up of 114 instructional modules:

- Radiation Physics.
- Radiation Protection I.
- Principles of Process Instrumentation.
- Heat Transfer and Fluid Flow.
- Introduction to Nuclear Systems.
- Instrumentation and Control of Reactors and Plant Systems.
- Reactor Operations.
- Reactor Safety.
- Reactor Auxiliary Systems.
- Power Plant Systems.
- Radiation Detection and Measurement.
- Reactor Physics.
- Power Plant Chemistry.
- Introduction to Quality Assurance/Quality Control.
- Metallurgy and Metals Properties.
- Mechanical Component Characteristics and Specifications.

Availability: Instructional modules are available individually or by courses from:

Technical Education Research Center - Southwest
4201 Lake Shore Dr., Suite 111
Waco, Texas 76710

Telephone (817) 772-8756

Printed:

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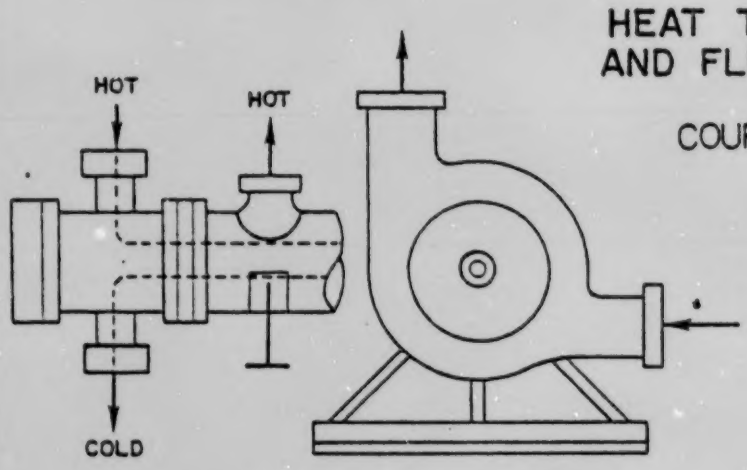
NUCLEAR TECHNOLOGY

MODULE 4-1 BASIC PROPERTIES OF FLUIDS. -

GEORGE J. STOLL, P.E.



HEAT TRANSFER AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE MODULES

COURSE 4. HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

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Technical Education Research Center
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INTRODUCTION

The rate of heat release and consequent power generation in a given reactor core is limited by thermal rather than by nuclear considerations. An unusual feature of a nuclear reactor is that there is no theoretical upper limit to its rate of energy release due to fission.

Thus, nuclear reactor core design depends as much on heat removal capability as on nuclear considerations.

This module examines basic properties of fluids used for removal of heat from nuclear reactor cores.

MODULE PREREQUISITES

The student should have completed a basic course in algebra, with a working knowledge of the metric system and the solving of simple equations. Also, the student should have received meaningful instruction in laboratory safety.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain principal differences between liquids and gases.

2. Define terms describing properties of fluids, including density, specific weight, specific heat, heat of fusion and heat of vaporization.
3. Explain viscosity.
4. Explain principles of buoyancy in terms of Archimedes' Principle.
5. Determine specific weight of a liquid.
6. Determine specific heat of a material.
7. Determine latent heat of vaporization of water.
8. Define, with appropriate English and SI units:
    - Heat.
    - Temperature.
    - Specific heat.
    - Calorie.
    - Btu.
    - Specific weight.
    - Buoyancy.
9. Convert temperature from Celsius to Fahrenheit degrees (and vice versa).

CLASSIFICATION OF MATTER

Any substance that can be weighed or that occupies space is called "matter." Solids, liquids and gases represent the three "states" of matter. One state of matter may be changed to another: iron (a solid at room temperature) becomes liquid when heated to a sufficiently high temperature. Solids occupy a definite volume and have a definite shape. Liquids occupy a definite volume, but take the shape of containing vessel. Gases not only take the shape of the containing vessel, but also expand and fill the vessel, no matter what its volume or configuration.

In solids, the atoms cling firmly together and do not change their relative positions readily. Hence, solids have a definite shape. In liquids, the force of attraction between the constituent atoms and molecules is less than in solids, and they slide over, under and around one another quite easily. Molecules in gases move so freely that they separate, leading to indefinite expansion and motion.

Plasma, which is a completely ionized gas (separated into individual atoms and electrons), does not fit easily into any of these categories. It is often called a "fourth state of matter." A viscous liquid flows slowly (e.g., heavy oil or molasses). If a liquid flows easily, it is said to have "mobility" or low viscosity. Viscosity can be considered as a resistance to flow, akin to an internal friction.

Heat promotes mobility in a fluid. It causes molecules to move more rapidly. For example, water changes to a solid (ice) at temperatures below 32°F (0°C); above this temperature, it is liquid (water) until its temperature reaches 212°F (100°C); at that point it changes to gas (steam).

THERMOMETRY

A device, which uses the principle of volume change, is the thermometer; it consists of a glass tube with a reservoir bulb at one end. The bulb and a part of the tube are filled with a fluid, frequently mercury or red alcohol. The tube is so minute that only a tiny fraction of the liquid leaves the bulb, even when the fluid level is near the top of the tube.

When the bulb is immersed in melting ice, the fluid level takes up a certain position, which never varies. In the Celsius scale, this position is defined as the zero of temperature (0°C).

Similarly, when the thermometer bulb is surrounded by vapor of boiling water at standard atmospheric pressure, the fluid expands until its upper level in the tube reaches another fixed position. This point is taken, arbitrarily, to be 100°C. The length of tube between the two fixed reference points on the Celsius scale is divided into 100 equal divisions, each of which, by definition, is one Celsius degree (1°C).

The Fahrenheit scale is based on two other "fixed" levels. The boiling point of water at standard pressure is 212°F, and its freezing point is 32°F. The difference between these two temperatures, 180 Fahrenheit degrees, corresponds to 100 Celsius degrees (Figure 4-1-1). Thus, to convert from Celsius temperature, T_C, to Fahrenheit temperature, T_F, one can use the simple Equation 4-1-1:

$$T_F = 1.8\ T_C + 32°F. \qquad \text{Equation 4-1-1 (Equation = Eq.)}$$

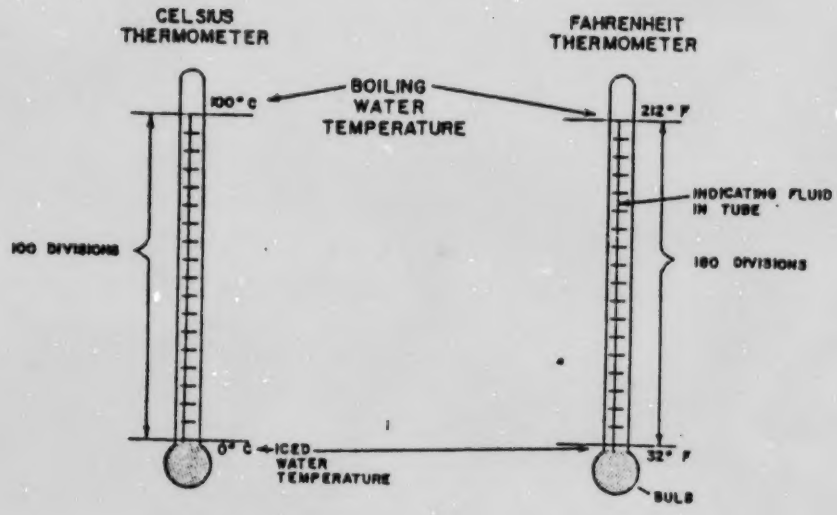


Figure 4-1-1. Comparison of Celsius and Fahrenheit temperature scale.

Thus, at 100°C,

$$T_F = 1.8(100°) + 32°$$

$$= 180° + 32° = 212°F.$$

One Fahrenheit degree is equivalent to 5/9 of a Celsius degree.

DENSITY

The mass of a unit volume of a substance is called its density. The unit volume selected for use in the English system is one cubic foot. In the metric system, it is one cubic centimeter. Hence, density is expressed in pounds per cubic foot (lbs/ft^3) or in grams per cubic centimeter (g/c^3) in these two systems of units.

To find the density of any substance, one first weighs it. Then, one finds its volume, either by direct measurement or by an indirect method such as finding the volume of water it displaces. Next, its weight is divided by its volume to find the weight of a unit volume.

A simple formula for use in solving problems involving density is given in Equation 4-1-2. Rho (ρ) is usually used to represent density, M represents weight or mass, and V represents volume, therefore:

$$\rho = \frac{M}{V}, \text{ or } \rho V = M \qquad \text{Eq. 4-1-2}$$

that is, density = $\frac{\text{mass}}{\text{volume}}$ (or density x volume = mass).

The density of water has been found to be 62.4 lbs/ft^3 in the English system. In the metric system, the density of water is defined as one gram per cubic centimeter, or 1 g/c^3. Commit these quantities to memory!

SPECIFIC WEIGHT OF LIQUIDS

The weight of another liquid relative to the weight of an equal volume of water is called its specific weight (sp. wt.), which has no units (it is merely a ratio).

Below are several methods of making this evaluation.

THE BOTTLE METHOD

A small flask, called a pycnometer (Figure 4-1-2) is

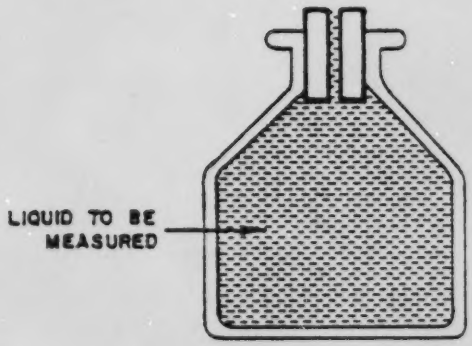


Figure 4-1-2.
Pycnometer used for determining specific weight.

first weighed. It is then filled with water and again weighed. Next, after drying, it is filled with the unknown liquid whose specific weight is desired and weighed a third time. By subtracting the weight of the empty bottle from each of the latter weighings, one can determine the weight of water that the bottle holds as well as the weight of an equal volume of liquid of unknown specific weight.

The bottle shown in Figure 4-1-2 has a stopper made of ground glass, which fits tightly. The tiny hole through the stopper makes it easy to fill the pycnometer with exactly the same volume of liquid each time. The mathematical definition of specific weight is given in Equation 4-1-3:

$$\text{Specific weight} = \frac{\text{weight of liquid "x"}}{\text{weight of water}} \text{ constant volume.}$$

Eq. 4-1-3

LOSS OF WEIGHT (OR BULB) METHOD - BUOYANCY

When a body is wholly or partly immersed in a fluid at rest, the fluid exerts pressure on every part of the body's entire surface contacting the fluid. The pressure is greater on the parts more deeply immersed. The result of all the forces is an upward force called buoyancy (of the immersed body). The magnitude and direction of this resultant force can be determined. "The buoyant force on a floating or submerged body is equal to the weight of the liquid displaced." This phenomenon is known as Archimedes Principle. An example of this principle follows:

EXAMPLE

Given: A tank filled to the top with water; a piece of wood 1 ft^3 in volume; water weighs 62.4 lb/ft^3.

Find: Weight of water displaced.

Solution: Fully submerge wooden block in water; weigh displaced water. Also, force required to completely

submerge 1 ft^3 is 62.4 lbs; i.e., buoyant force also is equal to weight of water displaced.

If one now submerges a body of liquid, as in Figure 4-1-3, the force at the top, F_D, is equal to the pressure P_D, or mathematically as Equation 4-1-4:

$$F_D = P_D \times A_D. \qquad \text{Eq. 4-1-4.}$$

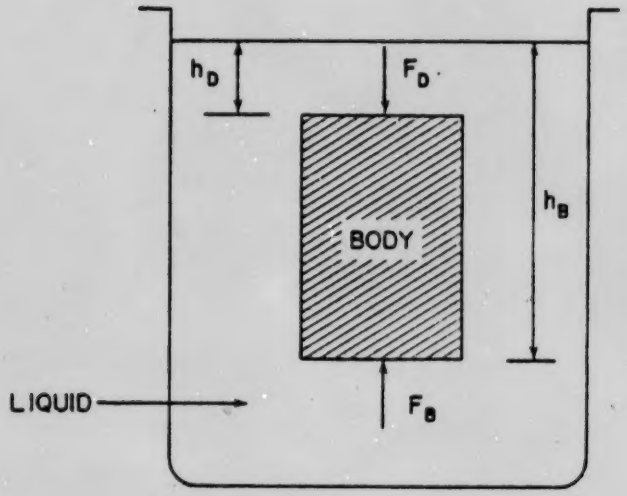


Figure 4-1-3. Buoyancy forces on a submerged body.

On the bottom surface, the force F_B equal to the pressure P_B over area A_B:

$$F_B = P_B \times A_B.$$

The resultant upward force or buoyancy is, therefore:

$$F_B - F_D = (P_B \times A_B) - (P_D \times A_D)$$

and if $A_D = A_B$ then $F_B - F_D = A\ (P_B - P_D)$.

$(P_B - P_D)$ is numerically equal to the weight of a column of liquid of height $(h_B - h_D)$ for a unit area. However, a column of liquid of weight $A_\rho\ (h_B - h_D)$ has the same dimensions as the submerged solid $A\ (P_B - P_D)$. Therefore, the buoyancy force equals the weight of an amount of liquid equal in volume to the volume of the submerged body.

One sees that the force acts vertically up through the center of gravity of the fluid, before its displacement, which, in an immersed body, is called its center of buoyancy.

The denser the liquid, the greater its lifting force or bouyancy. Hence, one can determine the relative weight of two liquids by comparing their buoyant effects upon some unknown solid.

THE HYDROMETER METHOD

$$\text{Specific weight} = \frac{\text{depth a rod sinks in water}}{\text{depth a rod sinks in liquid "x"}}.$$

Eq. 4-1-5

A commercial hydrometer has a scale so graduated that the specific weight of the liquid in which it floats may be read directly (Figure 4-1-4).

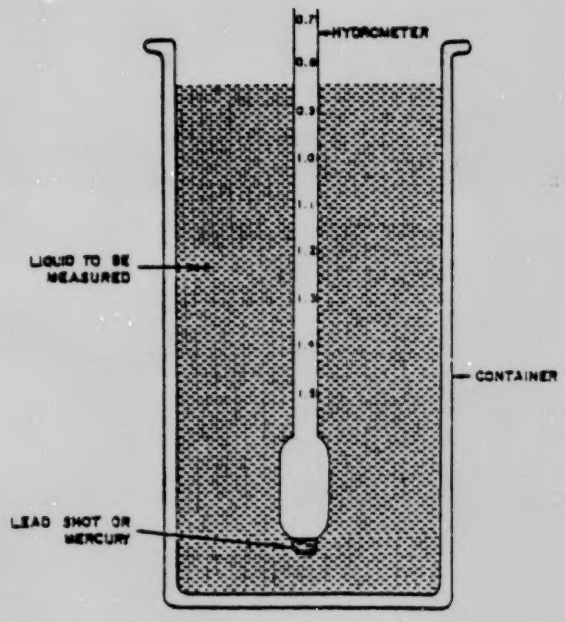


Figure 4-1-4.
Typical hydrometer for measuring specific weight.

The upper portion of the bulb is designed to increase the volume of the hydrometer, while the lower bulb is filled with shot or mercury so that the vertical position of the hydrometer is maintained as it floats. Hydrometers may be made for use with liquids less dense than water, or for those more dense than water. It is possible to have a hydrometer for use with either type of liquid.

Specific weight is frequently used to judge purity of substances, particularly liquids. For example, special hydro-

meters are available to indicate when an automobile storage battery needs recharging; this is accomplished by measuring the specific weight of the liquid in the battery.

VISCOSITY

Another liquid property is "surface tension," which acts as though there is a thin elastic film or membrane stretched over the liquid surface. Some liquids, such as oils, have high internal friction but low surface tension (compared with water). These liquids pour slowly and are called viscous liquids.

The viscosity of a liquid is normally found in two ways: 1) by counting the number of drops that pass through a small opening in one minute, or 2) the time it takes a ball to drop a given distance in a tube filled with the liquid. Then, the relative viscosities are found by comparing liquids of different viscosities and noting the relative time needed by balls of equal weight to fall through equal distances of these liquids.

A high viscosity liquid would be "thick" and slow flowing (crankcase oil). A low viscosity liquid would be "thin" and free flowing (water).

The viscosity of a liquid, denoted by the symbol η (eta), is measured in units called poise (force times time/unit area, or dyne/s/cm^2, in the English system): for convenience; frequent use is made of centipoise (10^{-2} poise) or micropoise (10^{-6} poise).

LAW OF HEAT EXCHANGE

When two substances of unequal temperature are mixed or brought together, the warmer one loses heat and the cooler one gains heat. In other words, heat flows from the hotter to the cooler substance.

To a first approximation, the number of heat units, denoted Q, lost by the hotter body, equals the number of heat units gained by the cooler body:

Heat Lost by the Hotter Body = Heat Gained by the Cooler Body,

$$Q_{Lost} = Q_{Gained} \qquad \text{Eq. 4-1-6}$$

SPECIFIC HEAT

Before entering into the description of heat, two important heat terms must be defined.

Gram calorie - the quantity of heat needed to raise the temperature of one gram of water from 15° to 16° Celsius (one degree).

British thermal unit (Btu) - the amount of heat required to raise the temperature of one pound of water from 60° to 61° Fahrenheit (one degree). One Btu equals 252 calories. (One calorie equals approximately 4×10^{-3} Btu.)

From the definition of a calorie, it can be seen that the

heat capacity of water is one and (defining "specific" as meaning a ratio) the specific heat (denoted C_p) of a substance is the ratio of its heat capacity to that of water. Furthermore the mass (in grams of a liquid) multiplied by the change in its temperature (in degree Celsius) multiplied by the specific heat of liquid equals calories as given below:

$$Q = M \times C_p \times (T_2 - T_1). \qquad \text{Eq. 4-1-7}$$

where

Q = heat lost (-) or gained (+) in calories (cal) by a body.

M = mass of liquid in grams, g.

T_1 = initial temperature, °C.

T_2 = final temperature, °C.

C_p = specific heat of liquid, $\frac{\text{cal}}{\text{g} \times \text{°C}}$.

If T_1 is greater than T_2, Q is a minus number, which means heat is being lost by the body or liquid.

Heat and temperature are not the same thing. When heat is supplied at the same rate for a given length of time to equal masses of "different" materials, starting at the same temperature, their final temperatures are generally different. Temperature is really relative, that is, something at a higher temperature is "hotter" than something at a lower temperature. Heat, on the other hand, is absolute.

If two different masses of the same material are given

the same quantity of heat, the increase in their temperatures will be different. The amount of heat needed to generate a given rise in the temperature of a body varies with the mass of the body and is a function of the substance of which it is composed.

Water has a higher heat capacity than nearly all other materials (1 cal/°C between 0°C and 100°C); brass has a heat capacity of only 0.09 cal/°C. The term specific heat is often used interchangeably with heat capacity.

Table 4-1-1 gives the specific heat values for a selected number of substances used in the nuclear energy field. The temperature (or range of temperatures) at which the measurements were made is specified in each case.

Some important consequences of heat are listed below:

Heat is the result of internal molecular motion.

Intensity of heat or temperature is measured in degrees, Fahrenheit (°F) or Celsius (°C). Quantity of heat is measured in calories or British thermal units (Btu).

The mechanical equivalent of heat is stated as follows: 778 ft/lb = 1 British thermal unit (Btu). In the metric system, 427 gram-meters of work are equal to 1 calorie.

There is a law of heat exchange: heat lost = heat gained, or Q lost = Q gained. (Equation 4-1-7).

The specific heat of a substance is the number of calories required to raise the temperature of 1 gram of that substance 1°C. Weight in grams multiplied by change in temperature (Celsius), multiplied by specific heat equals calories. Weight in pounds multiplied by specific heat equals Btu's: $Q = M \times C_p \times \Delta T$.

TABLE 4-1-1

SPECIFIC HEATS OF IMPORTANT MATERIALS

Substance	Specific Heat cal/g °C	Temperature Range of Specific Heat Values (°C)
Beryllium	0.425	0 - 100
Cadmium	0.055	28
	0.060	277
Carbon (graphite)	0.17	20
	0.25	138
Iron	0.115	100
	0.163	500
Lithium	1.041	100
Sodium (liquid)	0.295	20
	0.32	100
Silver	0.056	20
	0.058	200
Thorium	0.0276	0 - 100
Uranium	0.0292	100
Water	1.00	0 - 100
Zirconium	0.068	0 - 100

by specific heat equals Btu's: $Q = M \times C_p \times \Delta T$.

HEAT FUSION OR LATENT HEAT

The heat of fusion is defined as the number of calories needed to melt (change in state from solid to liquid) one gram of a substance without increasing its temperature. Therefore, if a few pieces of ice are placed on a pan and heat is added to the pan, with stirring, the ice will melt. One notes that the temperature remains at 0°C, and it does not rise until all

the ice is melted. Heat was being absorbed to merely melt the ice (change its state) since the temperature did not increase.

Experimental data shows that, to convert 1 gram of ice at 0°C into 1 gram of water at 0°C requires 80 calories of heat. Similarly, it requires 144 Btu's to change 1 pound of ice at 32°F into water at 32°F. These quantities are known as the latent heat of fusion of water.

Nearly all substances have characteristic melting points. These changes of state occur at transition temperatures involving definite heats of fusion. Table 4-1-2 gives melting points and heats of fusion for a selected list of materials. Note that, when a gas liquefies, it liberates exactly the same amount of heat needed to vaporize the liquid (latent heat of vaporization). Conversely, when a liquid solidifies, it liberates a heat of condensation equal to the heat of fusion required to melt the solid.

To find the number of calories needed to melt one gram of a solid, which is its heat of fusion, use the method of mixtures. Given that hot water melts ice, it is possible to find how many grams of ice can be melted by a known weight of water at a known temperature. To do so, the following information is necessary:

Weight of calorimeter (a device container for measuring heat gained or lost in calories).
Specific heat of calorimeter (generally marked on outside of calorimeter or provided by supplier).
Weight of water.
Weight of ice.
Initial temperature of hot water in thermal equilibrium with calorimeter.
Final temperature when all ice is melted.

TABLE 4-1-2

MELTING POINTS AND HEATS OF FUSION

Substance	Melting Point* (°C)	Heat of Fusion (calories/g)
Beryllium	1280	80
Cadmium	321	13.2
Carbon (graphite)	3700 (Sublimes)	....
Iron	1535	6.5
Ice	0	79.8
Lithium	186	160
Sodium (liquid)	98	28
Silver	960	25
Thorium	1820	....
Uranium	1130	....
Water	0	80
Zirconium	1840	

*At a pressure of 76 cm mercury (101,325 Pascals)

*At a pressure of 76 cm mercury (101,325 Pascals).
*Sublimination is a change of state directly from solid to gas without going through a liquid state.

EXAMPLE

Given: A calorimeter weighing 100 g, with a specific heat of 0.09 cal/g C°; it contains 400 g or 40°C water; 91 g of ice are introduced; when ice

is melted, temperature is 18.2°C.

Find: Heat of fusion of ice.

Solution: Both calorimeter and water loss heat as follows:

$M \times (T_2 - T_1) \times C_p =$
100 g x (18.2°C - 40°C) x 0.09 cal/g C° = Q
- 196.2 cal (lost by calorimeter)
400 g x (18.2°C - 40°C) x 1.00 cal/g C°
= -8720 cal (lost by water).
Total calories lost = -196.2 - 8720.0 = -8916.2 calories.
These 8916.2 calories did two things: first, they melted 91 grams of ice; second, they warmed the 91 grams of water thus formed from 0°C to 18.2°C.
91 g x (18.2°C - 0°C) x 1.00
= 1656.2 calories gained by water
-8916.2 cal + 1656.2 cal = -7260 calories, lost to melt ice.
-7260 cal ÷ 91 g = -79.8 calories used to melt each g of ice.
Thus, the heat of fusion of water, ΔH_f, equals 79.8 calories. That is, 79.8 calories of heat must be added to melt one gram of ice at 0°C (79.8 calories is gained when 1 gram of liquid water is frozen at 0°C).

MELTING AND VAPORIZATION

When a body absorbs heat, its temperature "usually" rises; however, when heat is applied to melting ice or boiling water, the ice stays at 0°C until all of it has melted, while the boiling water remains at 100°C until all of it has

evaporated. Calorimetric measurements show that the heat of fusion required to melt a gram of ice at 0°C is ~ 80 calories, and the heat required to vaporize one gram of water (at normal atmospheric pressure) is 539 calories; this is called the heat of vaporization (ΔH_v) of water.

Similarly, practically all substances have characteristic melting and boiling points. The change of state occurring at these transition temperatures involves definite heats of fusion and vaporization.

HEAT OF VAPORIZATION

Evaporation is a cooling process, as it removes from a liquid its most energetic molecules. The average kinetic energy of those remaining molecules is less, causing a temperature drop.

If heat is steadily supplied to a liquid, the cooling due to evaporation can be offset, and a part of the exceptionally fast molecules capable of escape can be maintained. A definite amount of energy is lost to the liquid by the escape of its fastest molecules. Therefore, to maintain the temperature at a constant rate of evaporation, a definite quantity of heat energy must be supplied for each gram of liquid that "disappears." This is called the heat of vaporization.

If a basin of water is placed over a gas flame, bubbles of water vapor soon begin to form at the bottom of the basin. As these bubbles rise through the cooler layers of liquid above them, they collapse, causing the familiar "singing" so often noticed before liquids begin to boil. When the entire liquid is hot enough so that these bubbles reach the surface freely,

vaporization occurs throughout the liquid with visible disturbance. Such vaporization is called boiling, and the following statements apply:

Rate of evaporation or boiling increases with any increase in temperature.

Rate of evaporation or boiling increases as surface area of liquid increases.

Rate of evaporation or boiling increases when atmospheric pressure is reduced.

Rate of evaporation of water decreases when humidity of air increases.

Rate of evaporation increases with rate of change of air in contact with liquid surface.

Rate of evaporation of boiling water varies with nature of the liquid itself.

EXERCISES

1. Listed are three terms used to describe fluid properties. Circle any term that describes upward force a liquid exerts upon a body submerged or floating:

   Tension.
   Buoyancy.
   Specific gravity.

2. Circle correct statement(s) about the following question. The fact that liquids evaporate is evidence that:

   Liquid is viscous.
   Its boiling point is low.

Molecules are in motion.

3. Name a property of water that causes it to heat and cool slowly. _____
4. Calculate how many calories are needed to warm 500 g of iron from 15°C to 55°C.
5. A 200-g piece of metal, at a temperature of 100°C, is plunged into 400 g of water at 20°C; temperature rise of water is 28°C; calculate specific heat of metal.
6. Calculate (a) how many calories are required to melt 200 g of ice, and (b) how many more calories are required to heat resulting water to 55°C.
7. A Celsius thermometer registers 21°C; calculate equivalent Fahrenheit temperature.
8. A zirconium component in a reactor is heated from 30°C to 450°C; calculate how much heat per kilogram of metal is absorbed.

1	pycnometer.
1	triple beam balance.
1	set of weights.
1	set weighted rods.
2	hydrometer jars.
1	all purpose hydrometer.
1	commercial hydrometer.
1	assortment of liquid solutions.
1	boiler, steam.
1	assortment of rubber tubing.
1	water trap.
1	assortment of glass tubing.
1	calorimeter.
1	thermometer.
1	hot plate or Bunsen burner.
1	length of twine.
1	aluminum block (stamped "A").
1	copper block (stamped "C").
1	steel block (stamped "S").

DETERMINATION OF SPECIFIC WEIGHT OF A LIQUID (TWO METHODS)

BOTTLE (PYCNOMETER) METHOD

1. Weigh a complete dry specific weight bottle (pycnometer + stopper).
2. Fill bottle with distilled water; be sure water is level with hole in top of stopper.
3. Wipe off thoroughly all water on outside of pycnometer; weigh again.
4. After water has been poured out, bottle should be rinsed internally two or three times with a liquid of unknown specific weight.
5. Fill pycnometer with unknown liquid; weigh in same manner as in paragraph 2. Subtract weight of empty flask from 1) weight of water and flask, and 2) from weight of liquid of unknown density and flask.
6. Find specific weight of unknown liquid by dividing its weight by weight of water (equal volumes).
7. Prcceed in same manner for any other unknown liquids.
8. Compare experimental results with accepted values from published data; record data on Data Table No. 4-1-1.

HYDROMETER METHOD

1. Put a hydrometer rod, weighted-end down, into a jar of distilled water; read and record number of centimeters submerged (Figure 4-1-5A).
2. Remove rod, wipe it dry and put it into jar containing liquid of unknown specific weight.
3. Read number of centimeters submerged (for both cases); record on Data Table No. 4-1-2.

4. Calculate specific weight of unknown liquid by dividing number of centimeters submerges in liquid by number of centimenters submerges in distilled water; record on Data Table 4-1-2.
5. Proceed in same manner to find specific weight of other liquids, as instructor directs.
6. Use "commercial" hydrometer (direct reading) to determine specific weight of each liquid used (Figure 4-1-5B): record values on Data Table 4-1-2.

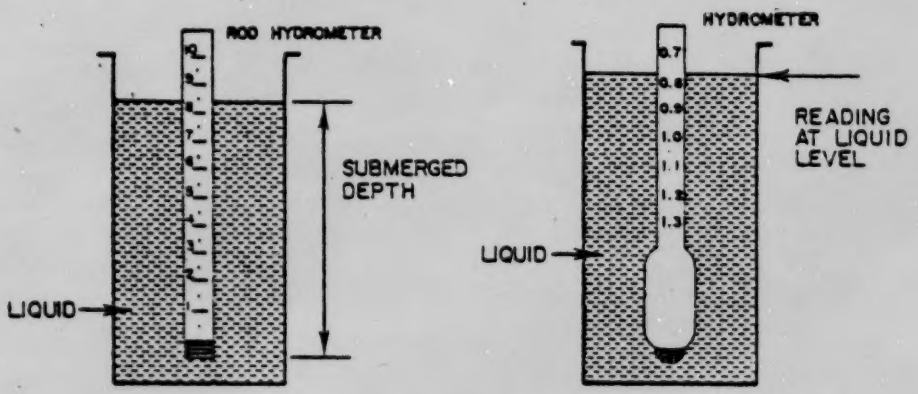


Figure 4-1-5. Hydrometer experiment.

DETERMINATION OF THE SPECIFIC HEAT OF A MATERIAL

1. Tie strong, light twine to block of aluminum, stamped "A;" weigh them together.
2. Put aluminum block in boiler half full of water (Figure 4-1-6); let string hang from stand so that warm block may be easily removed.
3. Light burner (or turn on hot plate, whichever is used).

4. While water in boiler is heating, weigh calorimeter.
5. Fill calorimeter with enough water to cover metal test blocks; weigh again. (Water used should be about 4°F cooler than room temperature.)

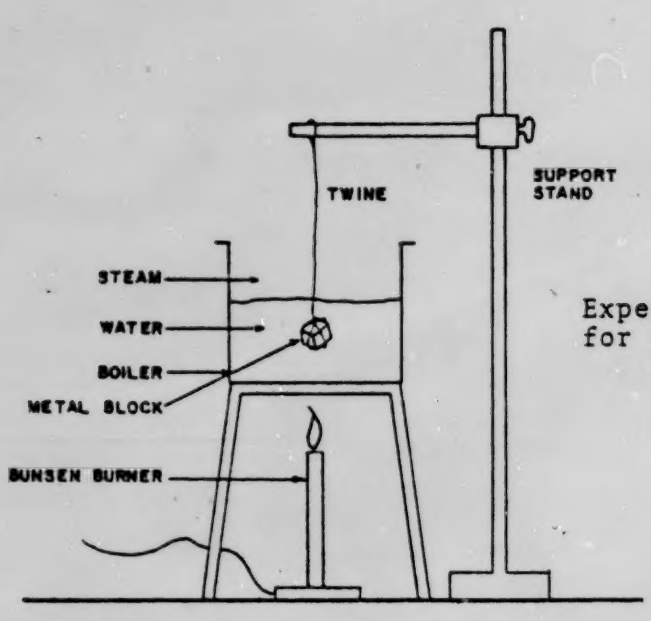


Figure 4-1-6. Experimental arrangement for determining specific heat of material.

6. Read temperature of steam arising from boiling water, which also will be temperature of aluminum block; record on Data Table 4-1-3.
7. Stir water in calorimeter with thermometer; prepare to take its temperature carefully just before aluminum is to be introduced, but while it is in thermal equilibrium with calorimeter.
8. Use twine to lift aluminum block just above surface of water; hold it in steam for a full half minute to ensure that aluminum is thoroughly dried.

9. Transfer aluminum block, as quickly as possible, to calorimeter of cold water.
10. Stir carefully with thermometer; also agitate water by lifting aluminum up and down slowly (do not remove it from the water); when temperature stops rising, read thermometer. Both calorimeter and water have gained same amount of heat as aluminum block lost. Determine specific heat of aluminum from this experiment.

CONDENSATION AND EVAPORATION HEAT TRANSFER

1. Light Bunsen burner (or hot plate) under steam boiler, which should be fitted with water trap (Figure 4-1-7) to ensure only dry steam enters calorimeter.

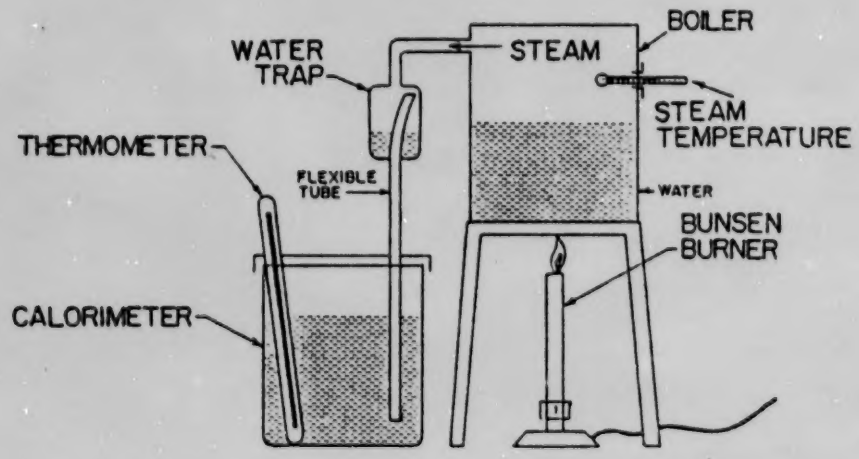


Figure 4-1-7. Boiler for heat transfer experiment.

2. While water is heating, weigh calorimeter.
3. Fill calorimeter two-thirds full of water at about 5°C; re-weigh.
4. Stir calorimeter water thoroughly with thermometer; take its temperature (estimate to tenths of a degree) just before steam is introduced.
5. Insert steam tube under water surface and pass a steady current of steam into water until temperature rises to about 35°C.
6. Remove steam line; stir water thoroughly and take final water temperature accurately.
7. Weigh calorimeter and contents (less thermometer). Increase in weight equals weight of steam introduced. Temperature of steam may be read directly from steam boiler. Student should remember that steam furnishes heat upon condensing, and that an equal weight of water at 100°C is formed. Water formed also furnishes heat while cooling to final temperature.
8. Determine heat of vaporization from this experiment and information recorded on Data Table No. 4-1-4.

DATA TABLE 4-1-1

BOTTLE (PYCNOMETER) METHOD

Data	Unknown Liquid #1_____	Unknown Liquid #2_____	Unknown Liquid #3_____
1. Weight of bottle =	g	g	g
2. Weight of bottle + distilled water =	g	g	g
3. Weight of distilled water is ② - ① ___ - _____ =	g	g	g
4. Weight of bottle + unknown liquid =	g	g	g
5. Weight of unknown liquid is ④ - ① ___ - _____ =	g	g	g
6. Specific weight =	____	____	____
7. Specific weight from accepted value tables =			

CALCULATIONS

Using specific weight formula $= \frac{\text{weight of unknown liquid}}{\text{weight of same vol. of water}}$

$= \frac{⑤}{③} = \frac{(\quad)}{(\quad)} = \_\_\_\_\_.$

Repeat calculations for other liquids of unknown specific weight.

DATA TABLE NO. 4-1-2

HYDROMETER ROD AND COMMERICAL HYDROMETER METHODS

	Unknown Liquids		
	#1_____	#2_____	#3_____
1. Length of hydrometer rod submerged in distilled water =	cm	cm	cm
2. Length of hydrometer rod submerged in unknown liquid =	cm	cm	cm
3. Specific weight =	____	____	____
4. Specific weight reading from commercial hydrometer submerged in unknown liquid	____	____	____
5. Difference between ③ and ④			
6. % difference	%	%	%

CALCULATIONS

Using specific weight formula

$$= \frac{\text{depth rod sinks in water}}{\text{depth rod sinks in unknown liquid}}$$

$$= \frac{①}{②} = \frac{(\qquad)}{(\qquad)} + \qquad .$$

Repeat calculations for liquids of unknown specific weight.

DATA TABLE 4-1-3

CALCULATIONS AND DATA NEEDED FOR DETERMINATION OF THE SPECIFIC HEAT OF ALUMINUM

Weight of Calorimeter _____ g

Specific heat of calorimeter _____

Weight of calorimeter and water _____ g

Weight of water _____ g

Weight of metal block _____ g

Original temperature of water and calorimeter _____ °C

Original temperature of metal _____ °C

Final temperature of water, calorimeter and metal _____ °C

Calories gained by calorimeter (wt. x temp. change x sp. ht.) _____

Calories gained by water (C_p = 1 cal/g°C) (wt. x temp. change x 1) _____

Total calories gained _____

Total calories lost (same as calories gained) (Wt. of metal x change in temp. x sp. ht.) _____

Calories lost by metal in cooling 1° _____

Calories lost by 1 g of metal in cooling 1°C (sp. ht.) _____

· DATA TABLE 4-1-3 (continued)

SPECIFIC HEAT OF METALS

Metal Block	Test	Weight of Metal Block (m_1) g	Weight of Calorimeter Empty (m_2) g	Weight of Calorimeter + Water	t_1 °C	t_2 °C	t_3 °C
Aluminum "A"	1						
	2						
Copper "C"	1						
	2						
Steel "S"	1						
	2						

m_3 = weight of water.

t_1 = temperature of calorimeter and water just before warm metal is put in.

t_2 = temperature of metal block just before it is placed into calorimeter water.

t_3 = final temperature reached by calorimeter water after hot metal block has entered water and thoroughly mixed.

C_p = unknown specific heat, C_{p2} specific heat of calorimeter, C_{p3} specific heat of water.

CALCULATIONS

From two basic equations:

$Q = m \times C_p \times (\Delta T)$ and

heat lost by metal block = heat gained by both calorimeter and water, we find

$m_1 \times C_p \times (t_3 - t_2) = m_2 C_{p2} (t_3 - t_1) + m_3 C_{p3} (t_3 - t_1)$.

Solve specific heat of unknown metal block for C_p.

DATA TABLE 4-1-4

CALCULATIONS AND DATA NEEDED TO DETERMINE THE LATENT HEAT OF VAPORIZATION

1. What is weight of empty calorimeter?
2. What is specific heat of calorimeter?
3. What is weight of water and calorimeter?
4. What is weight of water?
5. What is original temperature of water and calorimeter?
6. What is temperature of steam?
7. What is final temperature of water and calorimeter?
8. What is weight of water, calorimeter, and added steam?
9. What is weight of steam?
10. How many calories are gained by calorimeter? (wt. x temp. change x sp. ht.)
11. How many calories are gained by water? (wt. x temp. change x sp. ht.)
12. What is total number of calories gained:
13. How many calories are lost by steam in condensing and cooling to final temperature (same as cal gained)?
14. How many calories are lost by hot water? [(wt. of steam x (final temperature - 100) x 1.)]
15. How many calories are lost by x g of steam in condensing?
16. How many calories are lost by 1 g of steam during condensation?

DATA TABLE 4-1-4 (continued)
LATENT HEAT OF CONDENSATION AND EVAPORATION

	Test No.		
	1	2	3
1. Weight of calorimeter empty =	g	g	g
2. Weight of calorimeter full =	g	g	g
3. Weight of calorimeter = ② - ① =			
4. Temperature of calorimeter water before steam is introduced =	°C	°C	°C
5. Final temperature of calorimeter water after steam has condensed =	°C	°C	°C
6. Weight of calorimeter + water + condensed steam =	g	g	g
7. Weight of condensed steam = ⑥ - ② =	g	g	g
8. Latent heat of condensation =			

REFERENCE MATERIALS

Bureau of Naval Personnel. Fluid Power. From the Navy Training Course. Washington, DC: Department of Defense, 1970.

Harris, Norman C. and Hemmerling, Edwin M. Introductory Applied Physics. New York: McGraw-Hill, 1972.

1. List basic differences between a liquid and a gas:

2. Briefly describe properties of fluids listed (as given in this module):

   Density.

   Specific weight.

   Specific heat.

   Heat of fusion.

   Heat of vaporization.

3. A solid rectangular block measures 30 cm x 80 cm x 40 cm and weighs 510 kg; calculate its density in g/cm^3:

4. Convert block size (from 3 above) to inches; calculate its density in lbs/ft^3:

   Its specific gravity:

5. Briefly explain viscosity, as related to fluids, and how viscosity is measured:

6. Briefly explain basic principles relating to the following statements:

   A stone thrown into water sinks.

   A stone thrown into a pool of mercury floats.

7. Write a hypothetical lab test for determining specific weight of a metal object; describe, as a minimum, apparatus needed, items to be measured, calculations to be made, formulae to be used and test data to be tabulated:

8. Listed on the left below are seven items; listed on the right are item descriptions. Match each item with its description by placing its number in space in description.

1. Heat.	_____Degree of hotness or coldness related to a scale.
2. Temperature.	_____Weight of a liquid compared with weight of an equal volume of water.
3. Calorie.	_____Amount of heat required to raise 1 lb of water 1°F.
4. Specific weight.	_____There are 252 in a Btu.
5. Specific heat.	_____Number of calories required to raise 1 g of material 1°C.
6. British thermal unit.	_____Energy added or removed from an object, causing it temperature to rise or fall.
7. Buoyancy.	_____Upward force causing a balloon to rise in the air.
	_____Device for measuring density of a fluid.

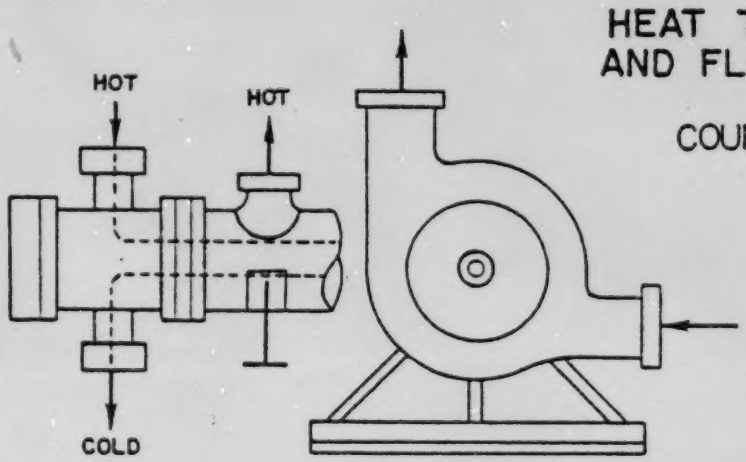
8. Convert (by calculation) temperatures listed to scales required (round out temperatures to the nearest 0.1°):

32°F	=	_____°C
32°C	=	_____°F
100°C	=	_____°F
100°F	=	_____°C
-32°F	=	_____°C
-32°C	=	_____°F
-10°C	=	_____°F
-2°C	=	_____°F

NUCLEAR TECHNOLOGY

MODULE 4-2 FLUID STATICS, -

GEORGE J. STOLL, P.E.



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE MODULES

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiation

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

Fundamental to a study of fluid behavior are concepts of force and pressure; therefore, this module includes a detailed discussion of these phenomena.

MODULE PREREQUISITES

The student should have completed Module 4-1, "Basic Properties of Fluids."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Demonstrate that static pressure is equal to specific weight times height.
2. Explain basic principles of hydraulic systems (Pascal's Law).
3. Calculate static pressure at any point in a hydraulic system (given fluid properties, specific weight and height).
4. Explain effects of specific weight and height on pressure within a submerged body.

5. Measure (with a Bourdon gage) static pressure at any point in a hydraulic system.

CONCEPTS OF FORCE AND PRESSURE

The general term "fluid" covers substances that lack rigidity; therefore liquids and gases are classed as fluids. Fluids cannot sustain a shape without external resistance from a vessel or container. A distinction between liquids and gases can be made, based upon an observation that liquids have surface. That is, the cohesive forces acting between molecules of a liquid are strong enough to give finite volume to a quantity of material; whereas gases have no such "natural" volume, but expand to completely fill any container in which they are placed. Both liquids and gases can be compressed more easily than solids.

What is pressure? Usually a push or pull measured in grams or pounds is defined as "force," and this force applied to a unit area is defined as "pressure." The unit of measurement of pressure is "pounds per square inch" or "grams per square centimeter." Total force, or a force acting against a total area, is measured in grams or pounds.

EXAMPLE

Bore a hole in the bottom of a tank containing liquid and the liquid flows out. Liquids push downward upon the bottoms of their containers (Figure 4-2-1), which is to be expected, because liquids have weight. If holes are bored in the sides of the tank, liquid will flow out through these openings; liquids exert pressure in all

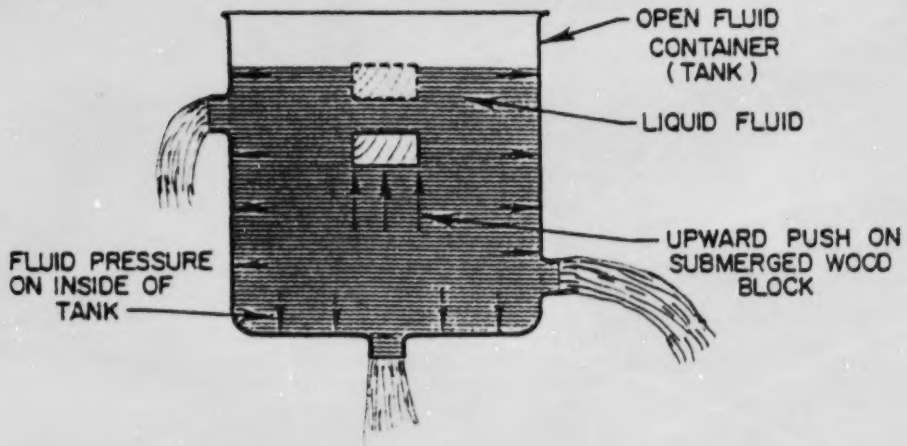


Figure 4-2-1. Pressure exerted by fluid in a tank.

directions. A piece of wood pushed down into a tank of water rises to the surface of the water as soon as it is released (force must be used to hold the block of wood in the water). Evidently, the water exerts an upward push on the block of wood. This upward push that a liquid exerts upon an object submerged in it causes some objects to lose all their apparent weight (to float); it causes dense objects to exert pressure in all directions - downward, sidewise and upward.

Pressure is defined as force per unit area, with the force applied perpendicular to the area:

$$P = \frac{F}{A}$$ Equation 4-2-1 (Equation = Eq.)

where

P = pressure, lbs/in^2.

F = force, lbs.

A = area upon which force is applied, in^2.

An object weighing very little can exert tremendous pressure if its force acts only on a small surface area.

EXAMPLE

Given: A record player needle tip that has a diameter of 0.002 inch and an arm that weighs 3 grams.

Find: Tip pressure.

Solution: Area of needle tip

$= 0.785\ (D)^2 = 0.785(0.002)^2$

$= 7.85 \times 10^{-1} \times 4.0 \times 10^{-6}$

$= 31.4 \times 10^{-7}$

$= 3.14 \times 10^{-6}$ in^2.

Force on tip

$= 3$ g $= 3 \times 0.0022$ lb

$= 6.6 \times 10^{-3}$ lb.

Pressure on tip

$$= \frac{F}{A} = \frac{6.6 \times 10^{-3}}{3.14 \times 10^{-6}}$$

$= 2.1 \times 10^{3}$

$= 2100$ lb/in^2.

On the other hand, the weight of 4.7×10^{16} tons of air creates only a relatively small pressure on the earth - the force is spread out over the entire surface of the globe.

For practical purposes, pressures can be expressed as so many atmospheres, where one atmosphere (atm) is normal atmospheric pressure, approximately 14.7 lb/in^2 or, in metric units, 1.013×10^5 Newtons/$meter^2$ or 1.013×10^6 dynes/$centimeter^2$. Another common unit of pressure, used especially in meteorology, is the "bar," which is 10^6 $dynes/cm^2$. [A millibar (mbar) is one thousandth of a bar.] Millimeter of mercury (mm Hg), used in many gas-law problems, is defined as $\frac{1}{760}$ atm (the pressure of a column of mercury 1 mm high). A mm Hg is also known as a "torr," named after Evangelista Torricelli, who invented the barometer in 1643.

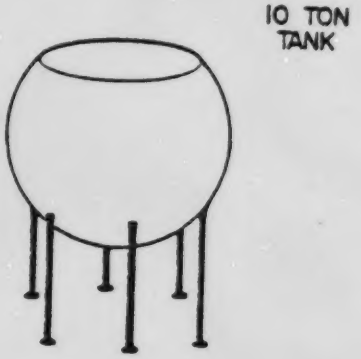
An "inch of water" is used in engineering for measuring relatively small deviations from normal atmospheric pressure, as in a household fan/duct system.

Pressure can be readily manipulated from one unit to another with the aid of a few conversion factors:

1 atm = 14.7 lb/in^2 (pounds/square inch)
= 1.013×10^5 N/m^2 (Newtons/square meter)
= 1.013×10^6 dyn/cm^2 (dynes/square centimeter)
= 76 cm Hg (centimeters of mercury)
= 760 mm Hg (millimeters of mercury)
= 34 ft of water (feet of water)
= 408 in of water (inches of water).

EXAMPLE

Given: Six concrete footings supporting a 10-ton tank, each support having 18 in^2 in contact with the ground:



Find: Pressure on one footing.

Solution:

$P = \frac{F}{A}$ (from Eq. 4-2-1)

$F = 10 \text{ tons} = 10 \times 2000 \text{ lb}$

$= 20{,}000 \text{ lb}$

$P = \frac{20{,}000 \text{ lb}}{6 \times 18 \text{ in}^2}$

$P/\text{footing} = 185.1 \text{ lb/in}^2$.

PRESSURE IN LIQUIDS AT REST

It is easy to compute pressure of a liquid on the bottom of a container: volume is base A times height h (Figure 4-2-2):

$$W = A \times h \times d \times g$$

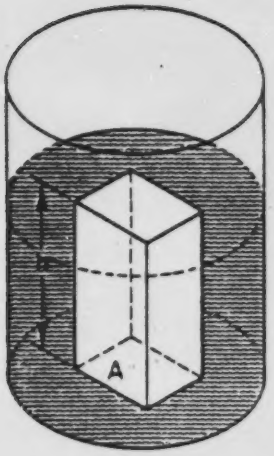


Figure 4-2-2.
Liquid pressure.

where

d = density of liquid.
W = weight of liquid.

Pressure P is force per unit:

$$P = \frac{A \times h \times d \times g}{A} = h \times d \times g. \quad \text{Eq. 4-2-2}$$

Because g is the gravitational constant, pressure of a uniform liquid depends on its height and density above a measured point.

EXAMPLE

Given: To fight fires in a power plant, water must be supplied at 150 lb/in^2.

Find: How high this reservoir must be above the plant.

Solution:

$$P = h \times d \times g$$

$$150 \frac{lb}{in^2} = \frac{h \times 62.4\ lb/ft^3}{144 \frac{in^2}{ft^2}}$$

$$150 \times 144 = h \times 62.4\ ft$$

$$h = \frac{150 \times 144}{62.4}\ ft$$

$$h = 346.1\ ft.$$

A liquid takes the shape of its container; therefore, liquid pressure is expected to be independent of direction, and from this the following "laws of liquid pressure" can be deduced:

Liquid pressure is directly proportional to depth of liquid.

Liquid pressure is directly proportional to density of liquid.

Liquid pressure is independent of area or shape of container; it is also independent of direction.

The terms "direct proportion" and "inverse proportion" are frequently used when talking about pressure. It can be said that two quantities are directly proportional to each other when an increase or decrease in one produces

a corresponding increase or decrease in the other. Conversely, it can be said that two quantities are inversely proportional to either when an increase in one produces a corresponding decrease in the other.

Refer to the formula for density:

$$d = \frac{W}{V} \qquad \text{Eq. 4-2-3}$$

where

W = weight.

V = volume.

It can be seen that an increase in W without a change in V causes an increase in d; an increase in V without a change in W causes a decrease in d. Thus, density of an object is directly proportional to its weight, and inversely proportional to its volume.

PRESSURE MEASUREMENT

In the real world, some convenient device must be used to measure pressure. One way in which this is done is with an "open manometer" (Figure 4-2-3). A manometer balances the pressure of water against a column of mercury. For example, if it were necessary to measure water pressure in a home faucet, it would be possible to attach the manom-

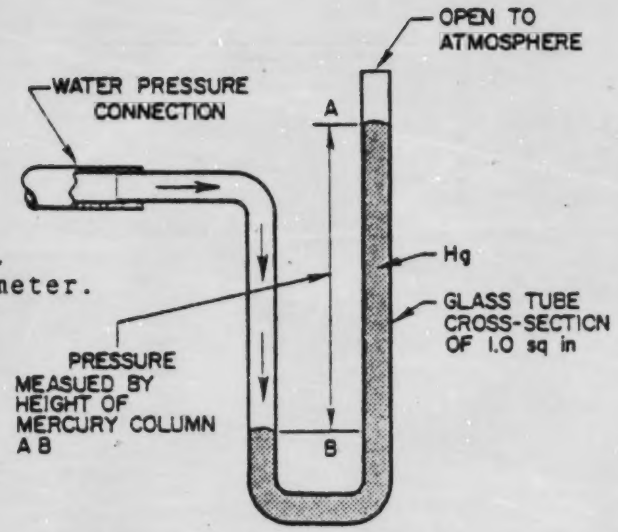


Figure 4-2-3.
Open mercury manometer.

eter to the faucet, and turn on the water and measure the pressure (it corresponds to height of mercury in column, AB). If the tube has a cross section of 1 square inch, weight of the mercury column in pounds equals pressure of water in pounds per square inch.

The most convenient and widely used industrial measuring device is a Broudon gage; pressure is measured by a spring gage, calibrated to read directly in pounds per square inch (Figure 4-2-4). Pressure of the liquid tends

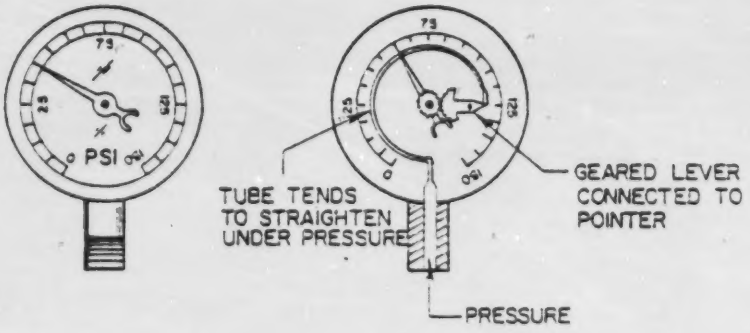


Figure 4-2-4.
Bourdon gage showing internals.

to straighten out a flat, curved tube, which is attached at one end to a lever and geared to a pointer.

A device used extensively for measurement of atmospheric pressure is the aneroid barometer (Figure 4-2-5).

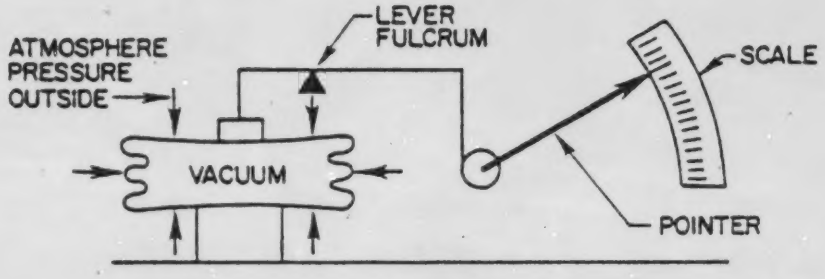


Figure 4-2-5. Aneroid barometer.

It depends upon the elastic properties of a sealed, evacuated can acted on by external (atmospheric) pressure. A lever arrangement increases the motion to a scale. On some instruments, a pen moves up and down on a rotating drum of paper resulting in a graphic representation of pressure over an extended time period.

Another term of liquid measurement is "head of water," which refers to the difference of level (Figure 4-2-6) between communicating pipes in a system.

Some applications of liquid pressure involve liquid seeking its own level. For example, the water gage on a boiler (Figure 4-2-7) indicates water level in the boiler by height of water in gage glass.

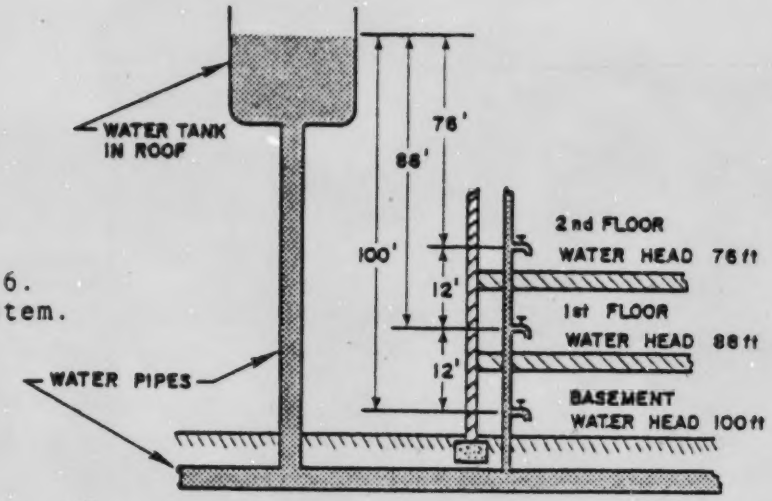


Figure 4-2-6.
Water pipe system.

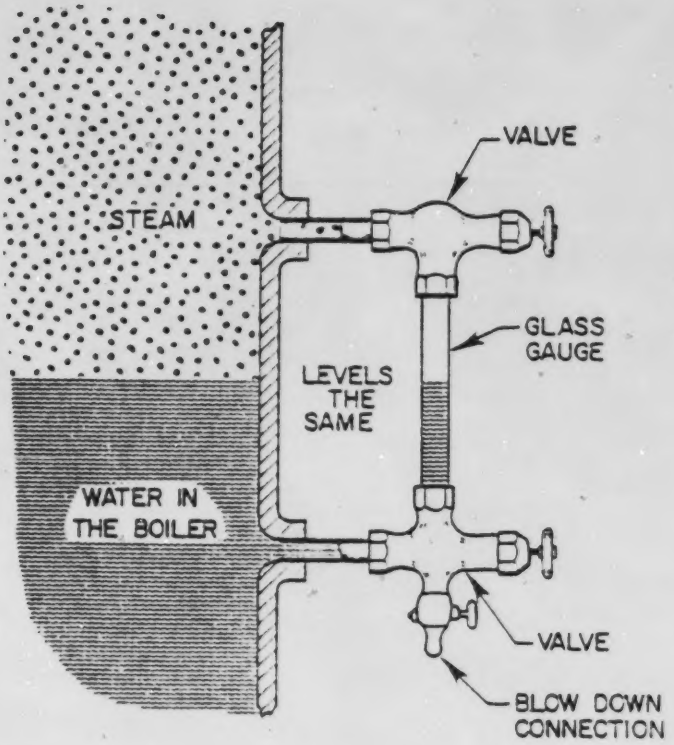


Figure 4-2-7.
Water level in
boiler drum.

HYDRAULIC SYSTEM PRINCIPLES

The behavior of hydraulic pressure changes was studied by French philosopher, Blaise Pascal (1623-1662), whose experiments are summarized in "Pascal's Principle:"

> Change of pressure exerted on any point in a confined fluid is transmitted undiminished in all directions to all points in the fluid. This pressure acts at right angles to every portion of the surface of the container, with equal force upon equal areas.

Because both liquids and gases are fluids, Pascal's Principle applies to both.

EXAMPLE

Piston A (Figure 4-2-8) with an area of 1 square

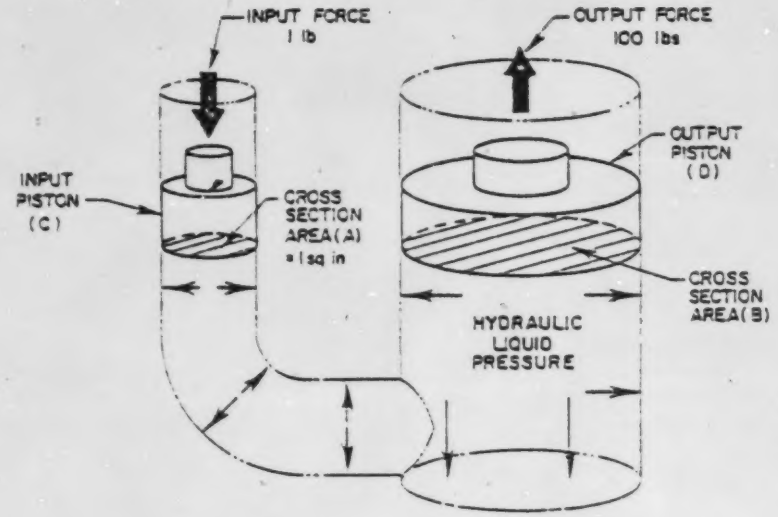


Figure 4-2-8. Pascal's pressure tank.

inch and piston B with an area of 100 square inches; a weight of 1 pound on piston C balances a weight of 100 pounds on piston D. But, a force of slightly over 1 pound, acting downward on piston C, lifts the 100-pound weight on piston D.

From this action, it would be possible to construct a machine for developing large forces. For example, if the large piston D were 1000 times the area of small piston C, the force on the small piston could be multiplied by 1000; however, as force in a device is multiplied, load distance and speed are diminished. (In other words, what is gained in force is lost in speed and distance.)

If, for example, piston C is forced down 10 inches, 10 cubic inches of liquid is forced from cylinder A into cylinder B. The 10 cubic inches of liquid forced into B spreads out over an area of 100 square inches; therefore, it raises the level and lifts piston B only $\frac{10}{100}$ (or 0.1) inch.

In the time required for C to move 10 inches, D moves only 0.1 inch, or just 0.01 as far as C. The force of 1 pound is multiplied 100 times by this machine, but the object to be lifted on the large piston moves $\frac{1}{100}$ as fast as the force applied to the small piston.

From the law of frictionless machines, in all mechanical devices the product of the acting force multiplied by the distance through which it moves equals the product of the resisting force multiplied by the distance through which it moves:

$$F_1 \times D_1 = F_2 \times D_2 \qquad \text{Eq. 4-2-4}$$

$$100 \times 0.1 = 1.0 \times 10.$$

A hydraulic press is a widely used application of Pascal's Principle (Figure 4-2-9).

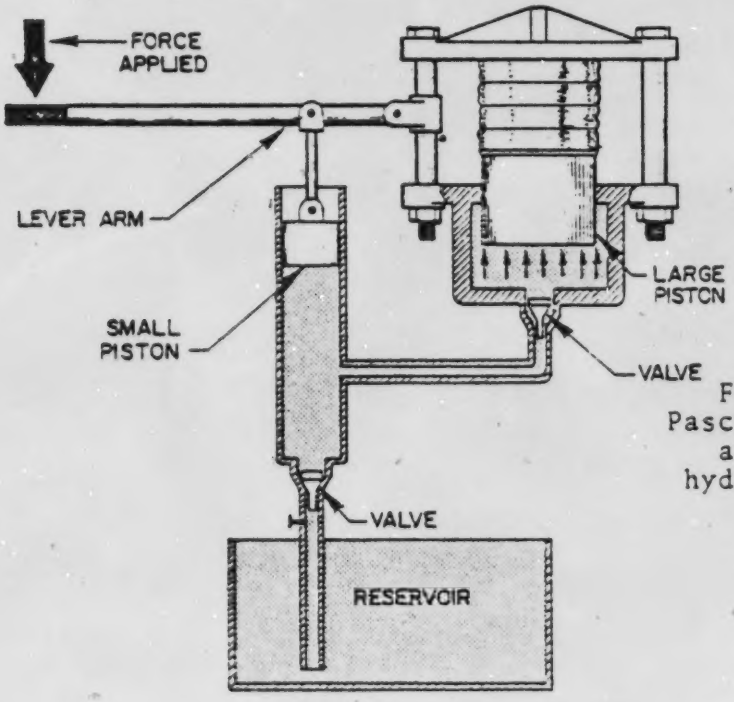


Figure 4-2-9. Pascal's principle applied to a hydraulic press.

There are two cylinders, a small one and a large one. In each cylinder is a tightly fitted piston. A force lever is attached to the small piston and, as the small piston is pushed down, some of the liquid from the small cylinder is forced into the large cylinder, lifting the large piston. As the lever is pumped up and down, it continues to

pump liquid from the reservoir and force it into the large cylinder. When pressure is to be released, the valve is opened and liquid flows back into the reservoir.

CALCULATIONS OF PRESSURE ON SUBMERGED BODIES

Each layer of liquid bears the weight of the layer above it. Therefore, the pressure of liquid increases in direct proportion to its depth. If, for example, (Figure 4-2-10), the unit pressure presses upon an area of 1 square

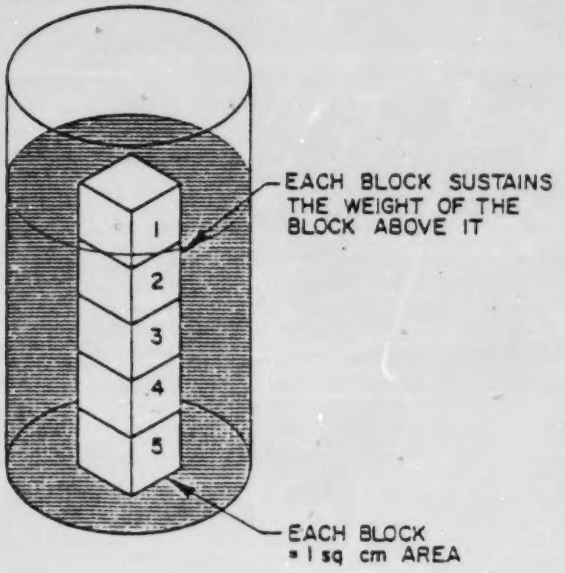


Figure 4-2-10.
Liquid pressure.

centimeter, then water, 1 cm deep, exerts a pressure of 1 g, which is the weight of 1 c^3 of water.

The pressure at a depth of 2 cm equals 2 g. For each cm increase in depth, the increase in pressure is

1 g; thus at 5 cm, the pressure is 5 g.

If the area acted upon is 1 square foot and the density of water is 62.4 lb/ft^3, then water 1 foot deep exerts a total pressure of 62.4 pounds.

Some liquids are more dense than others. Mercury weighs 13.6 times more than an equal volume of water; thus, mercury exerts more pressure than water for the same depth:

$$\text{Pressure } (P) = \text{depth } (h) \times \text{density } (d)$$

$$P = h \times d. \qquad \text{(From Eq. 4-2-2)}$$

EXAMPLE

Given: A diver dives to a depth of 150 feet; density of the water is 64 pounds/cubic foot (salt water).

Find: Pressure on each square inch of the diver's body.

Solution:

$$P = h \times d$$

$$\therefore P = 150 \times 64$$

$$P = 9600 \text{ lb/ft}^2$$

$$P = \frac{9600}{144} \text{ lb/in}^2.$$

EXERCISES

1. Define, by formulae and examples:
   Direct proportion.
   Inverse proportion.
   Pascal's Principle.
2. Why is it a good idea not to fill a vacuum bottle entirely full of hot liquid before putting in the cork?
3. What is the pressure, in g/cm^2, of a column of water 4 meters high?
4. Diameters of the two pistons of a press are 1 inch and 8 inches, respectively. What force, in pounds, is needed on the 8-inch piston to lift a weight of 144 tons with the 1-inch piston?
5. The surface of water in a standpipe is 196 feet above the level of a faucet. How much is pressure, in lb/in^2, at faucet?
6. What pressure is available when water head is 500 feet?
7. What pressure does a column of mercury 76 cm high (density = 13.7 g/cm^3) exert at the base?

MATERIALS

1 tall can (milk can).
1 plastic bottle and cork.
1 Pascal's vase, metallic diaphragm.
1 model hydraulic press and pressure gage.

PROCEDURES

1. Drill three or four holes at different heights in side of tall can; fill with water; measure horizontal distances water squirts from each hole. Is there any relationship between hole height and horizontal distance of squirt?
2. Fill bottle with water; insert tight cork; demonstrate that pressure in a confined liquid is distributed equally throughout the liquid by squeezing bottle at various places and watching bottle bulge. (This experiment should be performed alternately with Pascal's vase.)
3. Use a model hydraulic press; demonstrate mechanical advantages:
   - By means of piston diameters.
   - From effort distance and resistance distance.
   - From effort and resistance.
   - Measure oil pressure and record transfer for each experiment.

DATA TABLE

None.

Holman, J.P. Heat Transfer. 4th ed. New York: McGraw-Hill, 1976.

White, Harvey E. Modern College Physics. 6th ed. New York: D. Van Nostrand Company, 1977.

1. Demonstrate (with a sketch) that static pressure is equal to specific weight times height:

2. Briefly explain Pascal's Principle:

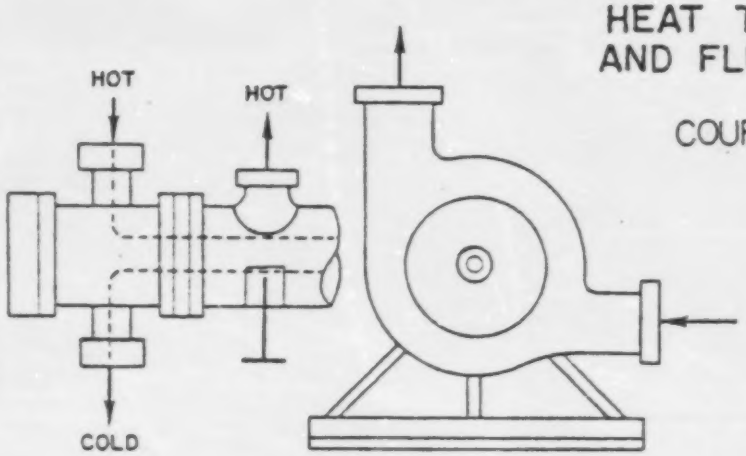
3. Calculate static pressure of a 20-inch diameter vertical pipe full of oil (density 80 lb/ft^3) 425 meters high (1 meter = 39.37 inches):

4. Briefly explain effects of specific weight and height on pressure within a submerged body (make necessary diagrams):

NUCLEAR TECHNOLOGY

MODULE 4-3 FLUID DYNAMICS. -

GEORGE J. STOLL, P.E.



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE MODULES

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiation

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

The subject of fluid dynamics (hydrodynamics) has challenged the world's greatest mathematicians and physicists. One, Daniel Bernoulli, propounded a fundamental equation from which many of the simpler fluid phenomena can be rationalized. Also, considerable practical data has been developed, tested and published in convenient form to enable technicians to understand and solve pipe flow problems.

MODULE PREREQUISITES

The student should have completed a course in algebra and one in high school physics (or equivalent).

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain significance of Bernoulli's equation.
2. Explain relationship between dynamic pressure and static pressure.
3. Explain relationship between dynamic pressure and flow.
4. Define laminar flow and turbulent flow, and state ma-

jor differences.

5. Define Reynolds number, give its significance and calculate its value.
6. Given Reynolds number and type of pipe, find friction factor, and state whether flow is laminar or turbulent.
7. Define head and relate to pressure units of psia, psig, "Hg and "H_2O.
8. Calculate friction drop of fluid flowing in a straight pipe of given dimensions.
9. Calculate pressure losses for fluid flowing in a pipe for changes in pipe direction and/or cross section.
10. Find appropriate fluid flow equations in references or textbooks.

OVERVIEW OF FLUID FLOW

Fluid flow can be "rotational" or "irrotational." To understand these terms, it is necessary to visualize what happens to an element of the fluid. If this element is visualized as a ball that moves without rotating, its motion is said to be irrotational. If it spins as it moves, it is rotational.

Irrotational flow is easier to define mathematically because rotational flow involves eddies, whirlpools and vortex motion.

Fluid flow can be compressible or noncompressible (liquids, usually, can be considered to be noncompressible). The density of gases, which (under normal circumstances) are highly compressible, can in some situations become practically noncompressible (e.g., the motion of air relative to wings of an aircraft at some speeds).

Fluid flow can be viscous or nonviscous; viscosity in fluids finds its counterpart as friction in solid motion.

Fluid flow can be steady or unsteady, when passing a given point, if all particles are traveling at the same velocity, the flow is considered steady. In unsteady flow, velocity is a function of time and varies erratically.

The study of fluid dynamics, for the most part, is limited to steady, irrotational, noncompressible, nonviscous flow.

In the eighteenth century, Daniel Bernoulli stated this principle: If the speed of a liquid passing through a tube increases at any point, the pressure of the liquid decreases at that point. As an example (Figure 4-3-1),

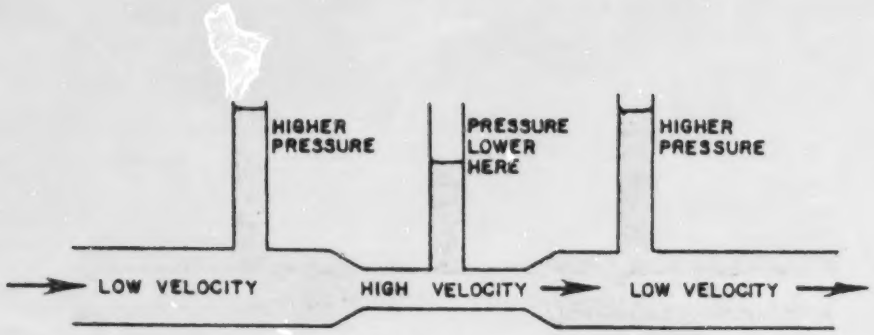

Figure 4-3-1. Venturi tube.

water flow is increased as it flows through the constricted section of a tube. (A tube having this kind of narrowing is called a Venturi tube.)

By noting the water levels in tubes (extending vertically from the Venturi tube), it becomes apparent that pressure decreases as water velocity increases. It is possible to calculate, from difference in pressure in the vertical tubes, velocity of the water in the horizontal tube. A meter that makes use of this principle is called a Venturi meter.

STREAMLINE AND TURBULENT FLOW

Bernoulli's Principle can be stated in equation form in a superficial case by considering four quantities: velocity v (ft/s), mass/unit volume d, pressure p (lbs/ft^2) and height above some reference level h (ft) of a liquid in "streamline" flow.

Streamline flow can be described as a fluid moving from point to point in a steady, irrotational, noncompressible, nonviscous flow.

Using an analogy, imagine two rows of boats moving

down a placid stream coming to a narrow section of the stream so that only one row can be accomodated; the boats have to move faster through the narrow section if streamline flow is to be achieved.

Turbulent flow is achieved when velocity of points in a fluid varies erratically from point to point as well as from time to time, as in rapids and waterfalls.

With these definitions in mind, Bernoulli's Principle can be restated:

> The quantity of a fluid is constant at every point in the fluid if the fluid is noncompressible and in streamline flow.

As the fluid flows from one place to another, speed v and pressure p are related:

$$\frac{1}{2} dv^2 + p = \text{constant.}$$ Equation 4-3-1 (Equation = Eq.)

If suffixes $_1$ and $_2$ are applied to different points in the system, but at the same elevation, the Principle is stated:

$$\frac{1}{2} dv_1^2 + p_1 = \frac{1}{2} dv_2^2 + p_2.$$ Eq. 4-3-2

If no change occurs in the liquid's velocity ($v_1 = v_2$), then Equation 4-3-2 becomes:

$$p_1 = p_2. \qquad \text{Eq. 4-3-3}$$

If, however, the pipe is not horizontal, pressure is changed because of elevation:

$$\frac{1}{2} dv_1^2 + p_1 + h_1 dg = \frac{1}{2} dv_2^2 + p_2 + h_2 dg. \qquad \text{Eq. 4-3-4}$$

If velocity is constant ($v_1 = v_2$) and dg is constant, then:

$$(p_1 - p_2) = (h_2 - h_1) \qquad \text{Eq. 4-3-5}$$

which relates pressure change to height-of-fluid change.

The action of a Venturi meter, the "curve" of a spinning ball, and the lift of an airplane's wing all are applications of Bernoulli's Principle.

A spinning ball moves along a curved path; the explanation lies in the fact that the ball drags the adjacent air around with it (Figure 4-3-2). At the top of the ball, air is moving with the air set up by the forward motion of the ball; at the bottom, it moves against these currents. As can be seen, the air at the top moves faster, so the pressure there is reduced.

Another application of Bernoulli's Principle is the suction pump, or aspirator, often used in a laboratory to produce a partial vacuum. The aspirator is attached to a

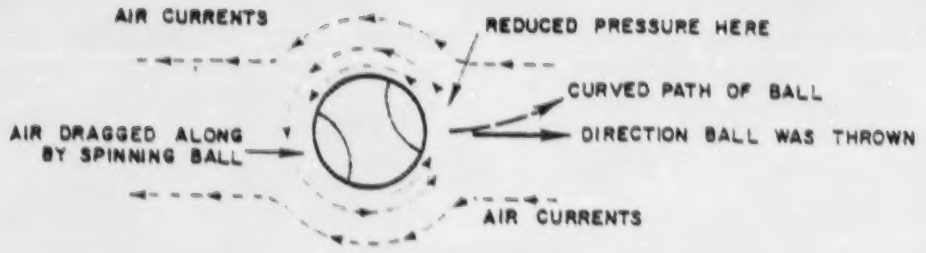

Figure 4-3-2. Curving baseball (an application of Bernoulli's Principle).

water faucet, with the vessel to be evacuated attached to the tube on its side (Figure 4-3-3). As water flows through

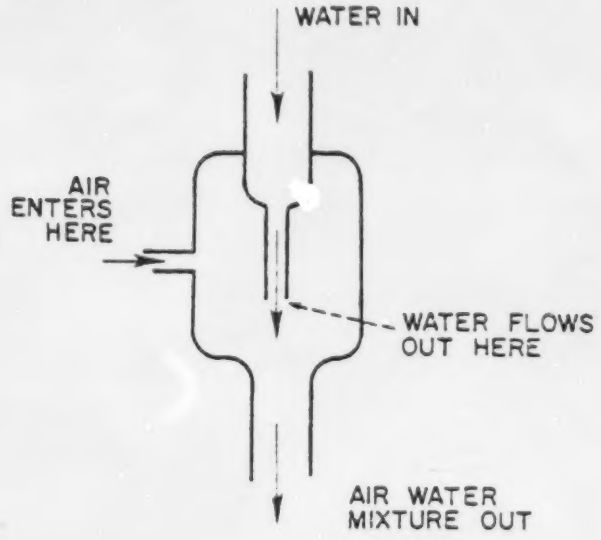

Figure 4-3-3. Aspirator. (Water drags air molecules along with it.)

the inner tube, it drags air molecules (from the vessel) along with it. Air in the vessel expands, thus more molecules are carried away by the running water. A very high vacuum can be produced quickly in this manner.

This principle is also exhibited in tall chimneys. When wind blows across the top of a chimney, the rapidly moving current of air carries along with it some of the

gas molecules from within the chimney (Figure 4-3-4). Gases

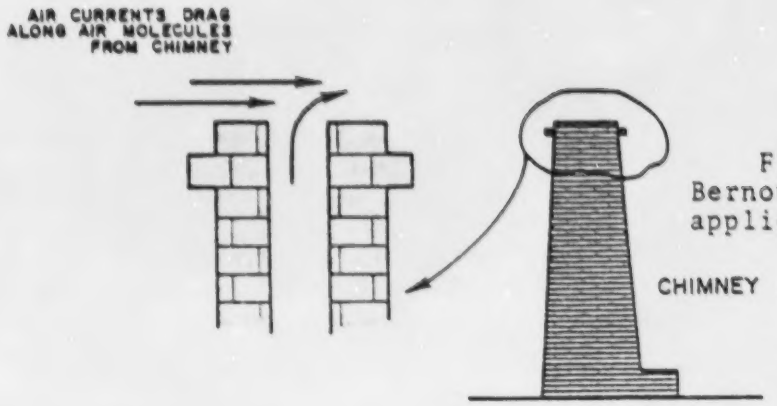

Figure 4-3-4.
Bernoulli's Principle
applied to a chimney.

expand within the chimney and their density decreases. A chimney draws better on a windy day.

An example of the "ejector principle" is illustrated by an atomizer (Figure 4-3-5), in which a small tube extends

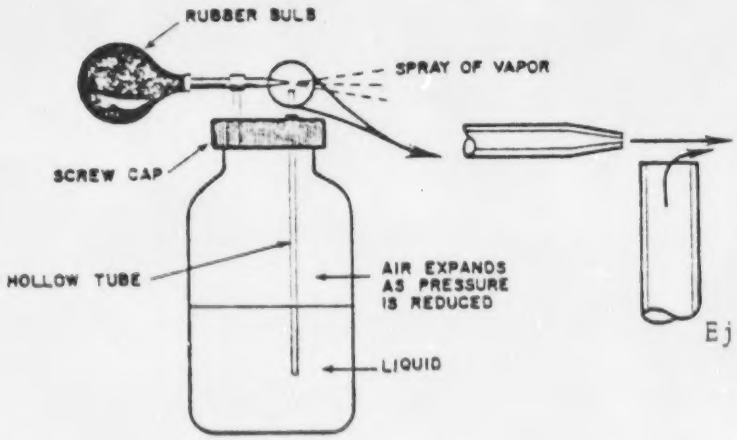

Figure 4-3-5.
Ejector principle.

through the stopper into the liquid in a bottle.

Forces resulting from pressure and velocity are used to support airplanes in flight. Another factor that plays an important part in the support of a plane in flight is an application of Bernoulli's Principle, which can be restated as follows:

> The high velocity of air moving past the upper surface produces low pressure against that surface (Figure 4-3-6).

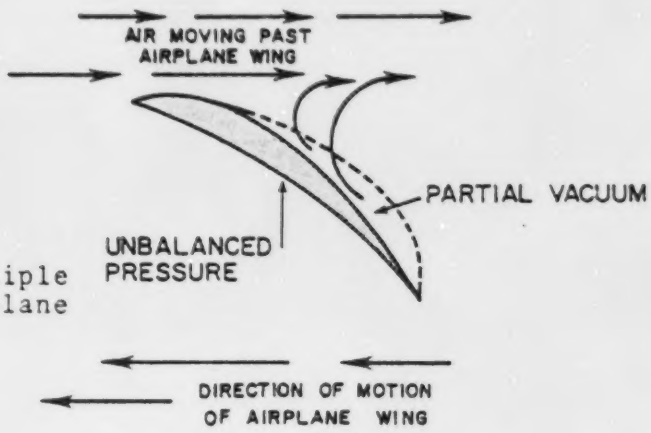

Figure 4-3-6. Bernoulli's Principle applied to an airplane wing.

The slight angle at which the airplane wing is set causes it to act as a type of Venturi tube. As air flows over the upper surface of the wing, its velocity increases and its pressure drops. So, an area of low pressure is formed. But on the undersurface of the wing a high atmospheric pressure is created. The wing tries to move away from the area of high pressure toward the low pressure, thus lift is produced.

REYNOLDS NUMBER

Fluid flow conditions are often characterized by a dimensionless group of parameters called Reynolds numbers:

$$Re = \rho \frac{vD}{\mu_e} \qquad \text{Eq. 4-3-6}$$

where

D = pipe diameter, ft.
v = avg. fluid velocity, ft/hr.
ρ = fluid density, lbs/ft^3.
μ_e = fluid viscosity, lb/hr-ft.

or

$$Re = 50.6 \frac{Q\rho}{d\mu} \qquad \text{Eq. 4-3-7}$$

where

Q = rate of flow, gal/min.
ρ = fluid density, lbs/ft^3.
d = internal diameter of pipe, inches.
μ = absolute viscosity, centipoise.

A Reynolds number represents a ratio of dynamics to viscous forces, used to determine whether fluid flow is

streamline or turbulent. Reynolds numbers less than 2100 are usually associated with streamline flow; a transition region exists between 2100 and 4000, which can be either streamline or turbulent; numbers greater than 4000 imply turbulent flow.

EXAMPLE

Given: Water at 90°F, flowing through 70 feet of 3-inch, standard wall pipe at a rate of 50 gallons per minute.

Find: Reynolds number, and if flow is streamline or turbulent.

Solution: From Equation 4-3-7,

$$Re = \frac{50.6\ Q\rho}{d\mu}$$

and

$Q = 50$ gal/min.

$\rho = 62.116$ lb/ft^3.

$d = 3.068$ in.

$\mu = 0.83$.

$$Re = \frac{50.6 \times 50 \times 62.116}{3.068 \times 0.83}$$

$Re = 61764$ which is > 4000

$\therefore$ flow is turbulent.

FRICTION FACTOR

Viscosity in a fluid is resistance to motion (internal molecular friction). In both liquids and gases, friction is proportional to velocity as long as the liquid is in streamline flow. In turbulent flow, friction increases at a much higher rate as velocity increases; therefore, it should be apparent from this that streamlining of planes, cars and other items to permit streamline flow at high velicity and to combat friction (Figure 4-3-7) is profitable economics.

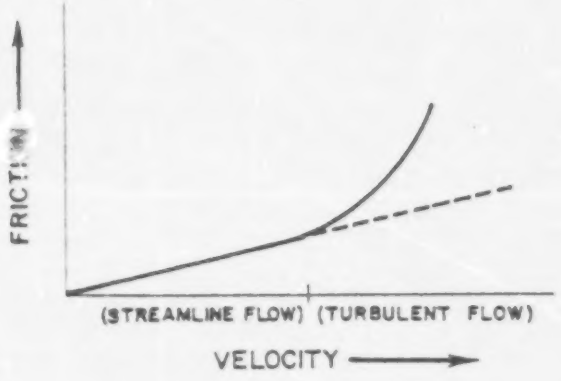

Figure 4-3-7. Friction versus velocity.

Viscosity, and therefore liquid friction, decreases as temperature rises; however, the opposite is true for gases.

Real fluids flowing through a pipe show a decrease in pressure in the direction of flow, which cannot be predicted by Bernoulli's equation. This "nonrecoverable" loss is caused by conversion of pressure energy to internal energy of the fluid, which is due to friction (irreversible)

between fluid and pipe.

Friction and other nonrecoverable losses are considered in an empirical fashion. The friction factor for streamline flow (Re < 2000) depends on Reynolds number only; turbulent flow also depends on pipe wall condition.

Between Reynolds numbers 2000 and 4000, there is an area known as the "critical zone" in which flow can be either streamline or turbulent, depending on factors such as changes of flow direction or obstructions. Friction factors in these regions are indeterminate and, at lower limits, are based on streamline flow; upper limits are based on turbulent flow.

Friction factors for pipes of small diameter usually are higher than pipes of a larger diameter of the same material; friction factors can be expected to rise with pipe age and use (due to buildup on inside pipe walls).

FRICTION DROP

Fluid flow is always accompanied by friction losses (due to viscosity), with the consequent loss of energy available for work; therefore, pressure drops in any line of flow.

At this point, the basics of pressure measurement of fluids can be defined (Figure 4-3-8). Gage pressure is measured above atmospheric pressure (standard atmospheric pressure is 14.696 pounds per square inch, or 760 mm of mercury).

To calculate pressure drop in a liquid line for stream-

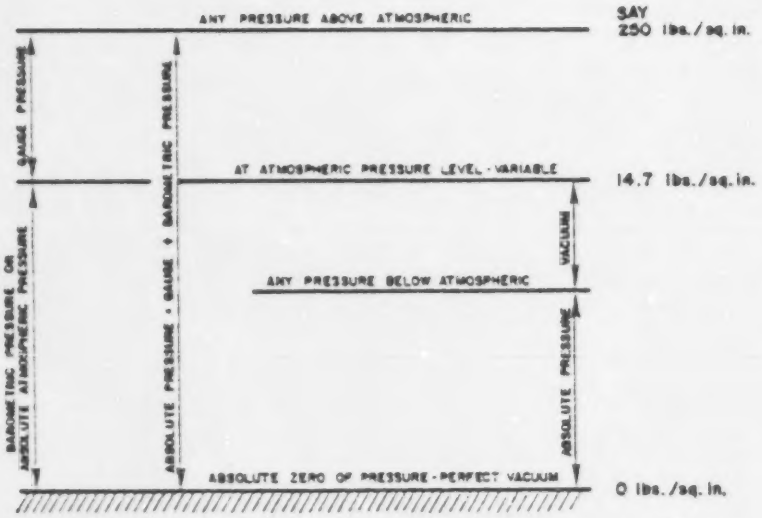

Figure 4-3-8. Relationship between gage and absolute pressures.

line flow (or at a Reynolds number of 2000 or less), the following formula may be used:

$$\Delta P_{100} = 0.0668 \frac{\mu V}{d^2} = 12.25 \frac{\mu q}{d^4} = 0.0273 \frac{\mu Q}{d^4}$$

Eq. 4-3-8

where

ΔP_{100} = pressure loss per 100 ft.

μ = absolute viscosity, centipoises.

V = mean velocity of flow, ft/s.

d = inside pipe diameter, in.

q = rate of flow, ft^3/s.

Q = rate of flow, gal/min.

With Reynolds numbers above 4000, where fluid flow is considered turbulent, pressure drop ΔP is calculated as follows:

$$\Delta P = 0.0216 \frac{f \rho Q^2}{d^5} \qquad \text{Eq. 4-3-9}$$

where

f = friction factor (see Appendix tables).

ρ = density, lbs/ft^3.

Q = rate of flow, gal/min.

d = inside diameter of pipe, in.

OTHER PRESSURE LOSSES

Industrial pipe installations nearly always contain valves and fittings, which add additional pressure losses into a system. These friction losses are called K factors.

Some representative K factor formulae, demonstrated in the Appendix, are taken from those established by consensus of the pipe and valve industry as well as the American Society of Mechanical Engineers. Published characteristics of valves, fittings and pipe afford quick and simple solutions to liquid flow calculations.

EXERCISES

1. Explain (in terms given in this module) why water seeks its own level.
2. If a Frisbee is thrown horizontally, with a counter-clockwise spin, does it go left or right?
3. Why does a chimney "draw" better on a windy day?
4. Why should a chimney top be higher than any part of the roof of a building?
5. Besides the Bernoulli Principle, what other factor figures in atomizer action?
6. Water at 60°F flows through 290 feet of 2-inch standard clean steel pipe (smooth wall) at a rate of 75 gallons per minute. Use Equation 4-3-7; find Reynolds number, friction factor and pressure drop per 100 feet.

MATERIALS

Several lengths of transparent plastic pipe, flanges, bends.
50-gallon measuring drum.
Rubber hose.
Hose clamp.
Dye nozzle.
Blue dye.
Stopwatch.
Pump source.
Several pipe orifices with varying hole sizes.

1. Given required information by instructor, calculate friction drop of fluid flowing in a straight pipe and pressure losses for fluid flowing in a pipe with at least three different valves installed.
2. Make up a straight length of transparent plastic pipe; put several bends in it (Figure 4-3-9) and two orifice plate gates.

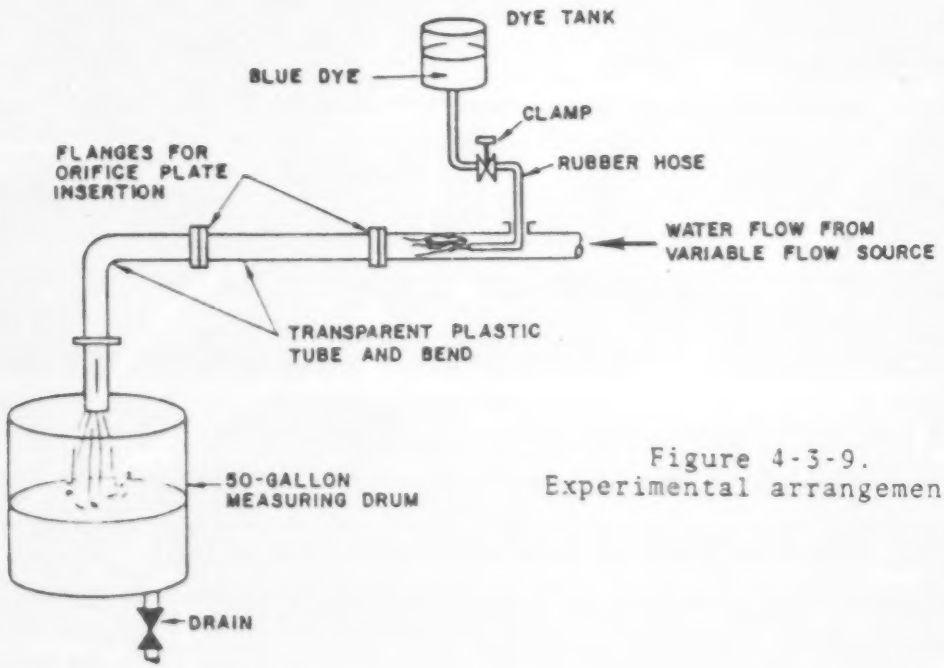

Figure 4-3-9.
Experimental arrangement.

3. Connect pipe to a water flow system; introduce (into the start of the pipe system) a thin stream of blue dye

so that flow pattern of the water can be observed along straight portion.

4. Use Data Table 4-3-1; calculate Re for several water flows; observe when dye stain shows a change in turbulence.
5. Add several orifices with larger and smaller openings; observe water flow pattern.

DATA TABLE 4-3-1

Exp. No.	Pipe Diameter (Ins)	Viscosity of fluid Centipoise	Flow Rate Gals/Min	Fluid Density Lbs/Ft^3	Re *	Flow Streamline/ Turbulent	Flow Pattern Observations
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							

* Calculate from $Re = 50.6 \frac{Q\rho}{d\mu}$ Eq. 4-3-10

Zebrowski, Ernest, Jr. Physics for Technicians. New York: McGraw-Hill, 1974.

A P P E N D I X

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"K" FACTOR TABLE

Representative Resistance Coefficients (K) for Valves and Fittings

PIPE FRICTION DATA FOR CLEAN COMMERCIAL STEEL PIPE WITH FLOW IN ZONE OF COMPLETE TURBULENCE

Nominal Size	½"	¾"	1"	1¼"	1½"	2"	2½, 3"	4"	5"	6"	8-10"	12-16"	18-24"
Friction Factor (f_T)	.027	.025	.023	.022	.021	.019	.018	.017	.016	.015	.014	.013	.012

FORMULAS FOR CALCULATING "K" FACTORS FOR VALVES AND FITTINGS WITH REDUCED PORT

• Formula 1

$$K_2 = \frac{0.8 \sin\frac{\theta}{2}(1-\beta^2)}{\beta^4}$$

• Formula 2

$$K_2 = \frac{0.8\,(1-\beta^2)\sqrt{\sin\frac{\theta}{2}}}{\beta^4}$$

• Formula 3

$$K_2 = \frac{2.6 \sin\frac{\theta}{2}(1-\beta^2)^2}{\beta^4}$$

• Formula 4

$$K_2 = \frac{(1-\beta^2)^2}{\beta^4}$$

• Formula 5

$$K_2 = \frac{K_1}{\beta^4} = \text{Formula 1} + \text{Formula 4}$$

$$K_2 = \frac{K_1 = \sin\frac{\theta}{2}[0.8\,(1-\beta^2) + 2.6\,(1-\beta^2)^2]}{\beta^4}$$

• Formula 6

$$K_2 = \frac{K_1}{\beta^4} = \text{Formula 2} + \text{Formula 4}$$

$$K_2 = \frac{K_1 = 0.8\sqrt{\sin\frac{\theta}{2}}(1-\beta^2) + (1-\beta^2)^2}{\beta^4}$$

• Formula 7

• $K_2 = \frac{K_1}{\beta^4} = 2$ (Formula 3 + Formula 4) when $\theta = 180°$

$$K_2 = \frac{K_1 = 2\left[0.8\,(1-\beta^2) + (1-\beta^2)^2\right]}{\beta^4}$$

$$\beta = \frac{d_1}{d_2}$$

$$\beta^4 = \left(\frac{d_1}{d_2}\right)^4 = \frac{a_1}{a_2}$$

Subscript 1 defines dimensions and coefficients with reference to the smaller diameter.
Subscript 2 refers to the larger diameter.

SUDDEN AND GRADUAL CONTRACTION

If: $\theta \leq 45°$ ..... K_2 = Formula 1
$\theta > 45° \leq 180°$ ..... K_2 = Formula 2

SUDDEN AND GRADUAL ENLARGEMENT

If: $\theta \leq 45°$ ..... K_2 = Formula 3
$\theta > 45° \leq 180°$ ..... K_2 = Formula 4

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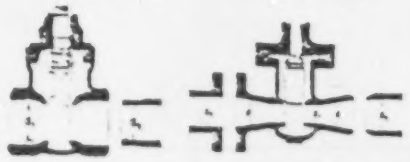
"K" FACTOR TABLE

Representative Resistance Coefficients (K) for Valves and Fittings

(For formulas and friction data, see page A-26)

GATE VALVES
Wedge Disc, Double Disc, or Plug Type



If: $\beta = 1$, $\theta = 0$ ..... $K_1 = 8\ f_T$

$\beta < 1$ and $\theta \leq 45°$ ..... K_2 = Formula 1

$\beta < 1$ and $\theta > 45°$ to $180°$ .. K_2 = Formula 2

SWING CHECK VALVES

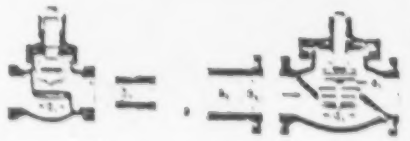
$K = 100\ f_T$

Minimum pipe velocity (fps) for full disc lift $= 35\sqrt{V}$

$K = 50\ f_T$

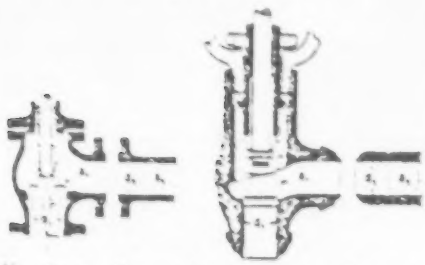
Minimum pipe velocity (fps) for full disc lift $= 48\sqrt{V}$

GLOBE AND ANGLE VALVES



If: $\beta = 1$ ..... $K_1 = 340\ f_T$

If: $\beta = 1$ ..... $K_1 = 55\ f_T$



If: $\beta = 1$ ..... $K_1 = 150\ f_T$ If: $\beta = 1$ ..... $K_1 = 55\ f_T$

All globe and angle valves, whether reduced seat or throttled,

If: $\beta < 1$ ..... K_2 = Formula 2

LIFT CHECK VALVES

If: $\beta = 1$ ..... $K_1 = 600\ f_T$

$\beta < 1$ ..... K_2 = Formula 2

Minimum pipe velocity (fps) for full disc lift $= 40\ f_T\sqrt{V}$

If: $\beta = 1$ ..... $K_1 = 55\ f_T$

$\beta < 1$ ..... K_2 = Formula 2

Minimum pipe velocity (fps) for full disc lift $= 140\ f_T\sqrt{V}$

TILTING DISC CHECK VALVES

	$\alpha = 5°$	$\alpha = 15°$
Sizes 2 to 3" $K =$	$40\ f_T$	$120\ f_T$
Sizes 10 to 14" $K =$	$30\ f_T$	$90\ f_T$
Sizes 16 to 48" $K =$	$20\ f_T$	$60\ f_T$
Minimum pipe velocity (fps) for full disc lift =	$80\sqrt{V}$	$40\sqrt{V}$

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1. Define and briefly explain significance of Bernoulli's Principle:

2. Briefly explain relationship between dynamic pressure and static pressure:

3. Briefly explain relationship between dynamic pressure and flow:

4. Define laminar flow and turbulent flow; give major differences:

5. Define Reynolds number (in terms used in this module):

6. Give significance of Reynolds numbers:

7. Calculate Reylonds number value, given d = 24 inches, v = 30 ft/s, ρ = (water) and μ = 0.83 centipoise:

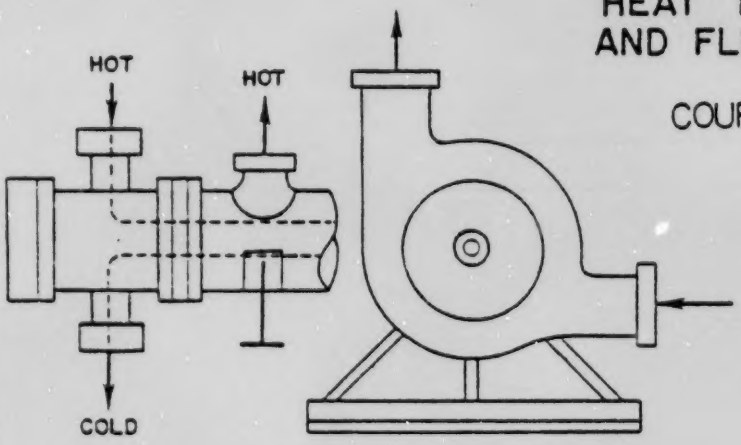
8. Given a Reynolds number of 6000 and a 3-inch diameter commercial steel pipe, find friction factor and note whether flow is laminar or turbulent:

9. Define head; relate head to pressure units of psia, psig, "Hg and "H_2O:

NUCLEAR TECHNOLOGY

MODULE 4-4 HEAT TRANSFER BY CONDUCTION. -

GEORGE J. STOLL, P.E.



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiation

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

In 1799, Sir Humphrey Davy proved that heat is a form of energy: he melted two pieces of ice by rubbing them together. (The kinetic theory of matter shows that temperature rises as velocity of its moving molecules increases; conversely, a decrease in molecular velocity causes a fall in temperature.)

Although heat and temperature are related, distinction must be made between them. The temperature of a body (measured in degrees) depends on average kinetic energy of all of its atomic structure. Heat of a body (measured in calories or British thermal units) depends on the total of all the kinetic energies of its atoms.

MODULE PREREQUISITES

The student should have a working knowledge of basic algebra, basic physics, the ability to solve arithmetical equations, and should have completed Modules 4-1, "Basic Properties of Fluids," 4-2, "Fluid Statics," and 4-3, "Fluid Dynamics."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define "heat flux," "critical heat flux," "heat capacity" and "resistance to heat transfer" in a typical fuel rod.
2. Write heat conduction equations, both for one dimension and for circular geometry, define terms and give significance of the equations.
3. By using reference materials, find thermal conductivity of at least ten given materials.
4. Given thermal conductivity and surface temperatures of a material, calculate heat flux in a one-dimensional slab (assuming no internal heat generation).
5. Given one surface temperature, thermal conductivity and heat flux, calculate one-surface temperature and internal temperatures.

HEAT

Certain terms, necessary for understanding this module and the phenomenon of heat, are defined below as they are used throughout the technology and industry:

Heat: Energy in transit due to a temperature difference between the "source" from which the energy is coming and a "sink" toward which it is going.

Heat capacity: The quantity of heat required to raise a unit mass of material one degree in temperature.

Heat conductivity: A measure of the ability of a material to conduct heat.

Heat flux: The amount of heat transferred across a surface of unit area in a unit time.

Heat resistivity: A measure of a body's ability to resist heat flowing through it equals the reciprocal of heat conductivity.

Temperature: A property of an object that determines direction of heat flow when that object is placed in thermal contact with another object. Usually measured in degrees Fahrenheit (°F), Celsius (°C), Kelvin (K or °K) or Rankine (°R).

Celsius: Temperature scale in which the freezing point of water (at 1 standard atmospheric pressure) is 0°C and boiling point is 100°C.

Fahrenheit: Temperature scale in which the freezing point of water (at 1 standard atmospheric pressure) is 32°F and boiling point is 212°F.

Kelvin: Absolute temperature scale in which units are equal [the temperature in °Kelvin (°K) = the

degrees in Celsius + 273.16].

Rankine: Absolute temperature scale in which temperature in °Rankine (°R) = the degrees Fahrenheit + 459.69. Also, at absolute zero, 0°R = 0°K.

British thermal unit (Btu): A unit of heat energy equal to heat needed to raise the temperature of 1 pound of water 1.0°F at one standard atmosphere.

Calorie (cal): A unit of heat energy equal to heat required to raise the temperature of 1 gram of water 1.0°C at one standard atmosphere.

Thermometers are used to measure temperatures, but they cannot be used to measure heat; also two substances may have the same temperature, but different quantities of heat. When buying coal, one may be interested in how many heat units are available, but not how high a temperature the burning coal is producing.

It is possible to measure (in a laboratory) the heat content of a weighed sample of fuel by finding the effect that it can produce. If it is found, for example, that one sample of coal heats one liter of water one degree, and that another sample of coal heats one liter of water two degrees, then the heat content of the latter is double that of the former. Again, pure water will be used as a standard in the definition of heat units.

HEAT UNITS

Individuals discuss calories a lot and the number that are eaten each day seem to be important. But what does the calorie mean to a physicist? As noted, a calorie is the quantity of heat needed to warm one gram of water through

one degree Celsius. Conversely, when one gram of water cools through one degree Celsius, it loses a calorie of heat. Therefore, to warm one gram of water ten degrees requires ten calories, and it takes ten calories to raise the temperature of ten grams of water one degree Celsius. (One gram of a good grade of soft coal produces about 8000 calories at is burns.)

The heat unit used in the English system is the British thermal unit (Btu), which is the amount of heat required to raise the temperature of 1 pound of water 1°F. (One Btu equals 252 calories.)

In a steam engine, when water is converted into steam in the boiler, the steam expands about 1700 times and exerts pressure in all directions and the steam is confined until it reaches a high pressure. From the boiler, it moves into the cylinder of a steam engine where it expands, pushes a piston back and forth in the cylinder, doing work. Btu's of heat energy (from burning coal or oil or nuclear fission) produce steam, and the steam, in expanding, produces mechanical energy as it drives the piston to and fro. (Similarly, mechanical energy is produced in a steam turbine as the steam expands through the turbine blades.")

Suppose that a pound of coal furnishes 14,500 Btu's. Find the total work (ft-lbs) that could be produced by a 100-percent efficient process.

(Use this conversion factor:

1 Btu = 778 ft-lbs.)

Work = 14,500 Btu x 778 ft-lbs/Btu

= 11,281,000 ft-lbs.

SPECIFIC HEAT

Water heats slowly, cools slowly and has the highest heat capacity of any ordinary substance. From the definition of the calorie, it can be concluded that the heat capacity of water is one (1). Since the word "specific" implies a ratio, then the specific heat of a substance is the ratio of its heat capacity to that of water.

Specific heat may be defined in terms of heat units. The specific heat of a substance is equal to the number of calories needed to raise the temperature of 1 gram of the substance 1°C. (In the English system, it is the number of Btu's required to raise the temperature of 1 pound of the substance 1°F.)

If 1 calorie heats 1 gram of water 1°C, then 100 calories should heat 100 grams of water 1°C; similarly, 100 calories should heat 1 gram of water 100°C. In all cases of this kind, it follows that: weight (in grams) times change of temperature (C) times specific heat = calories; or weight (in pounds) times change in temperature (F) times specific heat = British thermal units; or heat added (Btu's) = specific heat (Btu/lb/°F) x mass (lbs) x Δt (°F); or heat added (calories) = specific heat (calories/gram/°C) x mass (grams) x Δt (°C).

EXAMPLE

Find the heat (calories) needed to raise the temperature of 300 grams of iron through 50°C.

Given: Weight (300 grams); change in temperature (50°C); specific heat (0.113).

Solution: Weight x temp. change x specific heat
= 300 grams x 50°C x 0.113
= 1695 calories.

EXAMPLE

Find heat (calories) needed to be removed from 200 grams of water to cool it from 80°C to 20°C.

Given: Weight (200 grams); temperature change (60°C); specific heat (1.0).

Solution: Weight x temp. change x specific heat
= 200 grams x 60°C x 1.0
= 12,000 calories.

HEAT FLUX

Heat flux, Btu/hr-ft^2 is rate of heat transfer per unit of surface area, and in nuclear reactors heat fluxes are determined on a basis of fuel-rod surfaces. The fuel rod outside area, from top to bottom of the fuel pellet stack, is considered the heat transfer area for a single rod (Figure 4-4-1).

Therefore, the heat transfer area (A_h) is

$$A_h = \pi dL \text{ sq ft.} \qquad \text{Equation 4-4-1}$$

(Equation = Eq.)

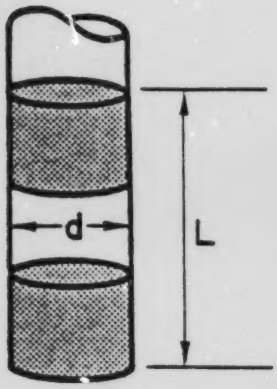


Figure 4-4-1.
Fuel pellet stack.

Then the average heat flux for a fuel rod is thermal output divided by heat transfer area:

$$"\bar{q} = \frac{\bar{q}}{\pi dL} \qquad \text{Eq. 4-4-2}$$

where

d = clad outside diameter.
L = pellet stock length.
$"\bar{q}$ = average heat flux, Btu/hr-ft^2.
$\bar{q}$ = average thermal output per rod, Btu/hr.

Furthermore, the average heat flux for the entire core is the total power output for the core, p (Btu/hr), divided by total heat transfer area, $\pi dL \times N$, where N = total number of fuel rods:

$$(\bar{q})_{core} = \frac{P}{\pi dL \times N}. \qquad \text{Eq. 4-4-3}$$

EXAMPLE

Compute average heat flux of a core, with the following data available:

Total heat output (MWt*) = 2441.
Number of fuel rods (N) = 32,000.
Outside diameter fuel rods (d) = 0.422 inches.
Pellet stack length (L) = 12 feet.

Solution:

$$"\bar{q} = \frac{\bar{q}}{\pi dL} = \frac{P}{\pi dL \times N}$$

$$= \frac{(2441)(3.413 \times 10^6)}{(32000)(\frac{\pi 0.422}{12})(12)}$$

$$= 190{,}000 \text{ Btu/hr-ft}^2.$$

---

* 1 megawatt = 3.413×10^6 Btu/hr.

CONDUCTION

Heat comes from several sources: the sun, chemical action, nuclear action and wasted work (friction). Heat can be transferred from one body to another - this is how

heat gets from furnaces in the basement to the rest of the house.

Heat can be transferred from one place to another in three basic and important ways:

Conduction.
Convection.
Radiation.

ATOMIC ACTION

How is heat conducted? If the bowl of a stainless teaspoon stands in a cup of hot coffee, the handle of the spoon becomes hot. When one end of a stove poker is held in live coals, the other end of the poker soon becomes too hot to be held comfortably. In some way, heat is conducted, or led, from the hot end of a solid to the cold end. Atoms of the live coals vibrate rapidly as they produce heat energy, and the atoms of the poker adjacent to the coals receive some of this heat energy, which they transmit along the poker to other atoms. Such transmission of heat from atom to atom is called conduction.

GOOD AND BAD CONDUCTORS OF HEAT - SOLIDS

Some solids are better conductors of heat than others. From the preceding module, it was learned that silver and iron are good conductors of heat. By use of a conductometer, the ability of solids to conduct heat may be compared (Figure 4-4-2) - rods covered with paraffin or paint change color when heated by steam passed through the base of the apparatus. The relative conductivity of metal rods can

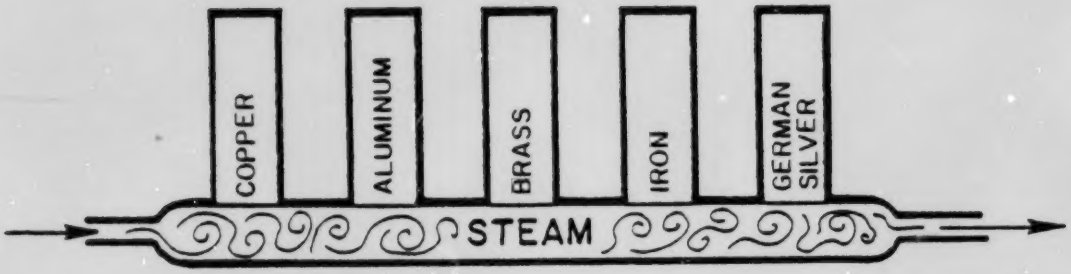


Figure 4-4-2. Some metals conduct heat better than others.

be determined by the rate at which the paraffin melts or the paint changes color. The order of conductivity of the five metals shown is as follows:

Copper.
Aluminum.
Brass.
Iron.
German silver.

Silver is the best conductor known, although it is not part of the test apparatus. Silver conducts heat more than 800 times as rapidly as water does, and almost 20,000 times as fast as air. Copper and aluminum are much better conductors than other common metals. German silver, which is an alloy of copper, zinc and nickel, is not a particularly good conductor. Metals generally conduct heat much better than woods or stone. Fibers used for clothing are rather poor conductors, although linen and cotton are better than wool and silk. Sawdust is a poorer conductor of heat than wood, because there are so many air spaces of insulation between the particles. For the same reason, furs and feathers are poor conductors of heat and, therefore, are excellent for cold climate clothing.

Liquids are relatively poor conductors of heat, as shown in the following example.

EXAMPLE

Put a piece of ice in the bottom of a test tube, fill tube two-thirds full of water (Figure 4-4-3). It is possible to boil the water at the top of the test tube for several minutes before the heat is conducted down the tube through the liquid to melt the ice. Water does conduct heat, but it is a poor conductor.

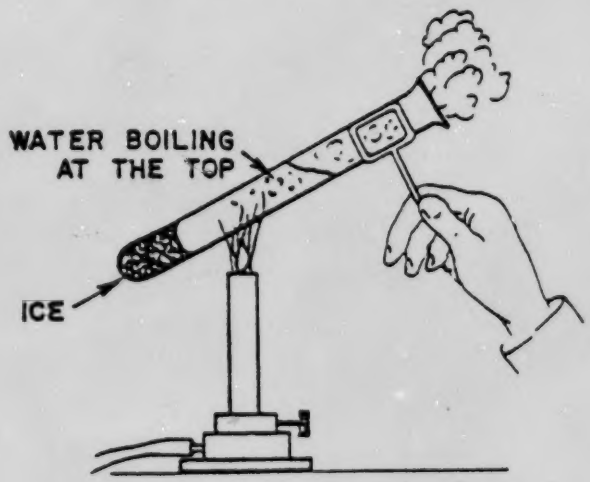


Figure 4-4-3.
Water is a relatively poor conductor.

A still more sensitive test can be made by using the apparatus shown in Figure 4-4-4. The bulb of an air ther-

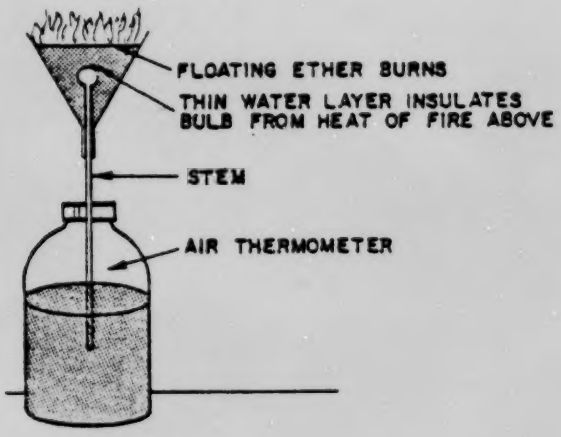


Figure 4-4-4.
Use of air thermometer to show that water is a relatively poor conductor.

mometer is surrounded with water in a large funnel and the stem of the thermometer dips into a colored liquid. Ether is poured on the surface of the water and set on fire. Although the air thermometer is extremely sensitive, there is little increase in air pressure, and the liquid column is lowered only slightly. This experiment, too, shows that water and other liquids are poor conductors of heat.

GASES

Gases are also very poor heat conductors, and it can be shown by experiment that gases are even poorer conductors of heat than liquids. The nonconducting layers of

air in porous solids are largely responsible for their poor conductivity. A vacuum or void is an efficient nonconductor of heat (called a heat insulator).

Conductivity affects our temperature sense. On a cold morning, the tiled floor of a bathroom feels much colder than a rug that covers a part of the floor; however, a thermometer would show that both have the same temperature. The tiling feels colder than the rug because it is a better conductor of heat: it takes heat from the foot faster than does the rug. A person who takes a pan of hot bread from an oven gets a more severe burn by accidentally touching the metal pan than by touching the bread in the pan. Both have the same temperature, but the metal is a better conductor, and transmits heat to the hand more rapidly. Again if both the pan and the bread were ice cold, the pan would feel colder to the touch than does the bread.

Winter clothing affords no warmth, but it does prevent the heat of the body from escaping and clothing made of the poorest conducting material seems warmest. Furs are very warm because they contain layers of nonconducting or insulating air. Two light garments are warmer than a single heavy one because there is a layer of insulating air between them. For the same reason, two light blankets are warmer than one heavy one.

HEAT FLOW AND THERMAL CONDUCTIVITY

If a flat plate is heated on one side and cooled on the other, heat flows through the plate from the hot side

to the cold one. The rate of heat flow, q, is conveniently expressed by the equation:

$$q = \frac{kS\Delta t}{\ell} = \frac{kS(t_1 - t_2)}{\ell}$$

Eq. 4-4-4

where

q = rate of heat flow, Btu/hour.
k = thermal (heat) conductivity
= Btu-in/hr-ft^2 - °F. (Note: Sometimes the thermal conductivity has units of Btu-ft/hr-ft^2 - °F or Btu/hr-ft - °F. In these cases the plate thickness to be used is given in feet, not inches.)
S = heating surface, sq ft.
Δt = temperature difference causing heat flow
= $(t_1 - t_2)$.
t_1 = temperature, °F, of heated side of plate.
t_2 = temperature, °F, of cooled side of plate.
ℓ = thickness of plate, inches.

As discussed previously, metals are good conductors and have a high thermal conductivity, whereas certain other materials are poor conductors with low thermal conductivities and are suitable for insulation. The thermal conductivities of several materials given in Table 4-4-1 can be used in practical examples and exercises.

Thermal (heat) conductivities of most pure metals decrease with increases in temperature, while conductivities

TABLE 4-4-1

THERMAL CONDUCTIVITY OF VARIOUS MATERIALS AT 32°F

Material	Thermal Conductivity k, $\frac{Btu\text{-}in}{hr\ ft^2\ °F}$
Metals:	
Silver (pure)	2844
Copper (pure)	2676
Aluminum (pure)	1404
Nickel (pure)	648
Iron (pure)	504
Carbon steel, 1% C	300
Lead (pure)	243.6
Chrome-nickel steel (18% Cr, 8% Ni)	112.8
Nonmetallic solids:	
Quartz, parallel to axis	288
Magnesite	28.8
Marble	14.4-20.4
Sandstone	12.72
Glass, window	5.4
First quality fire brick	4.5
Insulating fire brick	0.8
85% magnesia block	0.5
Maple or oak	0.15
Sawdust	0.41
Glass wool	0.26
Liquids:	
Mercury	56.88
Water	3.92
Ammonia	3.74
Lubricating oil, SAE 50	1.02
Freon 12, CCl_2F_2	0.50
Gases:	
Hydrogen	1.21
Helium	0.97
Air	0.17
Water vapor (saturated)	0.14
Carbon dioxide	0.10

of alloys may either increase or decrease. Thermal conductivities of insulating materials generally increase with increasing temperature.

Figure 4-4-5 shows the temperature gradient through a plate where heat flows from a heated side (at higher tem-

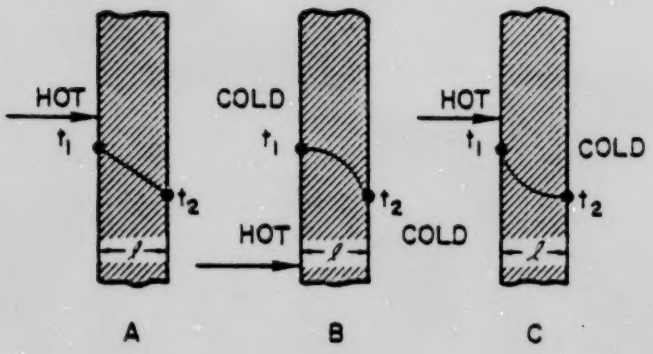


Figure 4-4-5. Diagrammatic temperature-thickness relationship.

perature) to a cooled side (at lower temperature). If the thermal conductivity of the material does not change with change in temperature, the temperature gradient will be a straight line.

For most heat transfer calculations it is sufficiently accurate to assume a constant conductivity corresponding to the average temperature of the material.

EXAMPLE

Find rate of heat flow (q) through a flat steel plate 1/2 inch thick, 1.0 foot^2 in area, with a temperature difference of 25°F across the surfaces.

Solution:

$$q = \frac{kS\Delta t}{\ell} = \frac{300 \times 1 \times 25}{0.25} = 30{,}000 \text{ Btu/hr.}$$

Eq. 4-4-4

Obtain k from Table 4-4-1.

CURVED WALL

When heat is conducted radially through a cylindrical wall, as in heat flow through the wall of a steam line from inside to outside of the pipe (Figure 4-4-6), the flat-plate

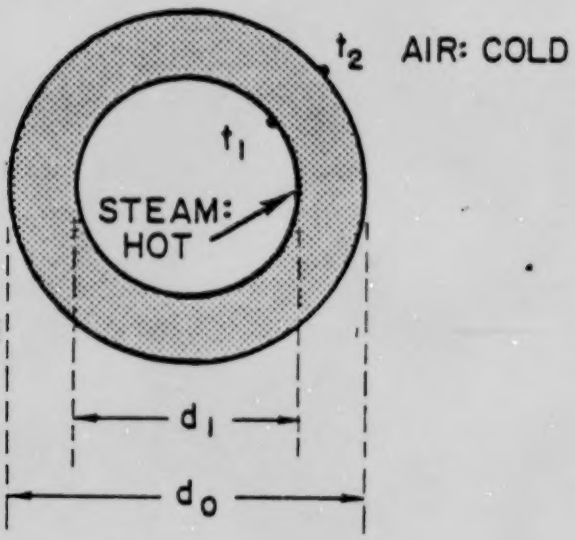


Figure 4-4-6.
Heat flow through cylindrical wall.

equation must be modified, since the heat-flow surface area, S, is no longer a constant but increases as the distance from the center of the pipe increases. For heat flow through a cylindrical wall, the equation is

$$q = \frac{k\,S(t_1 - t_2)}{\ell_e} = \frac{2k\,S(t_1 - t_2)}{d_o \ell_e\,(d_o/d_i)}$$

Eq. 4-4-5

where

d_o = outside pipe diameter, inches.

d_i = inside pipe diameter, inches.

The procedure for combining thermal resistances (Figure 4-4-7) of different materials (heat flow paths in series)

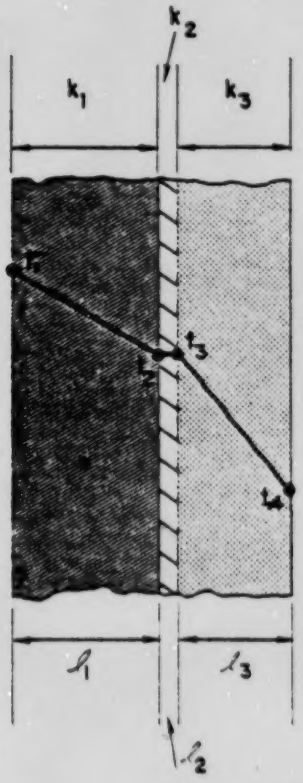


Figure 4-4-7.
Temperature distribution in composite wall.

into one overall resistance may be calculated as follows:

ℓ_1, ℓ_2, ℓ_3 = thickness in inches.

$$q = \frac{k_1 S \Delta t_1}{\ell_1} = \frac{k_2 S \Delta t_2}{\ell_2} = \frac{k_3 S \Delta t_3}{\ell_3} = \frac{Btu}{hr}$$

$$\Delta t_1 = \frac{\ell_1}{k_1} \times \frac{q}{S}$$

$$\Delta t_2 = \frac{\ell_2}{k_2} \times \frac{q}{S}$$

$$\Delta t_3 = \frac{\ell_3}{k_3} \times \frac{q}{S}$$

$$(t_1 - t_4) = \frac{q}{S} \times \left[\frac{\ell_1}{k_1} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3}\right]$$

$$q = \frac{S(t_1 - t_4)}{\frac{\ell_1}{k_1} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3}}.$$

This equation is a form of the equation $q = US\Delta t$, which is the equation for heat flow rate

where

U = combined conductance, $Btu/ft^2\text{-}hr\text{-}^\circ F$

$$= \frac{1}{\frac{\ell_1}{k_1} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3}}.$$

$\Delta t = t_1 - t_4$.

EXAMPLE

Find heat transferred through the wall of a furnace with these given parameters:

$S = 600\ ft^2$ wall surface.

$t_1 = 1080°F$, temperature of inside wall.

$t_o = 80°F$, temperature of outside wall.

$\Delta t = t_1 - t_o = 1000°F$, temperature difference.

$k_1 = 1.08\ Btu/ft^2\text{-}hr\text{-}°F/in$ for insulating firebrick.

$k_2 = 300\ Btu/ft^2\text{-}hr\text{-}°F/in$ for steel.

$k_3 = 0.5\ Btu/ft^2\text{-}hr\text{-}°F/in$ for insulation.

ℓ_1, ℓ_2, ℓ_3 = 4-in, 1/4-in and 3-in thicknesses, respectively.

Then

$$q = US\Delta t = \frac{600 \times 1000}{\frac{4}{1.08} + \frac{0.25}{300} + \frac{3}{0.5}}$$

$$= 437{,}956.2\ Btu/hr.$$

EXERCISES

1. Why should stove lifters and pokers have wooden handles?
2. How does snow protect grass in winter?
3. If solids are better conductors of heat than gases,

why does packing rock wool in the walls of houses help to insulate them?

4. A worker prepares tea by heating a cup of water with a 150-W electric immersion heater. The cup is glass and its mass is 7 oz; it holds 1/2 pint and is 4/5 full of water at 60°F. How long will it take it to bring the water and cup temperatures up to 185°F?
5. Architects in the U.S. often need to know the heat in Btu's that flows each hour through a sheet of area 1 ft^2 due to a temperature gradient of 1°F/in. By what factor should the coefficient (k) in the cgs unit (cal x cm/cm^2 x s x °C) be multiplied to obtain k in Btu x in/ft^2 x hr x °F?
6. One wall of a brick house is 10 feet x 30 feet x 8 inches thick. How many Btu's per day flow through the wall if inside temperature is 70°F and outside temperature is 10°F?
7. A lamp bulb inside a spherical glass shell 20 centimeters in radius and 0.5 centimeter thick radiates 100 W of thermal power. What is the difference in temperature between inner and outer surfaces of the glass?

MATERIALS

1 each carbon steel plate, wood plate, aluminum plate and firebrick plate: 12 in x 12 in x 1/4 in thick.
1 1000-watt hot plate.
1 watt meter.
1 surface thermometer.

PROCEDURES

1. Use surface thermometer: record temperature of carbon steel plate.
2. Place plate on hot plate which has been raised to operating temperature and connected to watt meter.
3. Use surface thermometer: record amount of time necessary to raise temperature 100°F.
4. Record amount of electricity used during this period.
5. Calculate heat flux.
6. Repeat steps 1 through 5 for each of these materials:
   Wood.
   Aluminum.
   Firebrick.
7. Discuss possible sources of errors and explain how errors may be minimized.

DATA TABLE

None.

REFERENCE MATERIALS

Gebhart, B. Heat Transfer. 2nd ed. New York: McGraw-Hill, 1971.

Perry, J.H. Chemical Engineer's Handbook. 4th ed. New York: McGraw-Hill, 1977.

1. Define "heat flux," "heat capacity," and "resistance to heat transfer" in a typical fuel rod:

2. Write the heat conductance equations - both for one dimension and for circular geometry, define the terms and give the significance of the equations:

3. From thermal conductivity tables provided by instructor write down thermal conductivity and units for the following:

   Silver (pure).

Copper (pure).

Carbon steel 1%.

Chrome nickel steel (18% Cr, 8% Ni).

Iron (pure).

Glass (window).

First quality firebrick.

Insulating firebrick.

85% magnesium block.

Glass wool.

Ammonia.

Carbon dioxide.

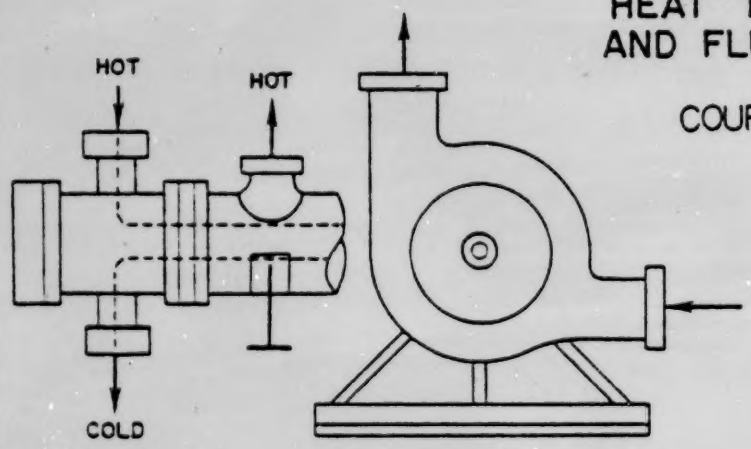
4. Given thermal conductivity and surface temperatures by instructor, calculate heat flux in a one-dimensional slab (assuming no internal heat generation).

5. Given one surface temperature, thermal conductivity and heat flux by instructor, calculate one-surface temperature and internal temperatures:

NUCLEAR TECHNOLOGY

MODULE 4-5 HEAT TRANSFER BY CONVECTION. -

GEORGE J. STOLL, P.E.



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE, WACO, TEXAS

COURSE MODULES

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids
MODULE 4-2 Fluid Statics
MODULE 4-3 Fluid Dynamics
MODULR 4-4 Heat Transfer by Conduction
MODULE 4-5 Heat Transfer by Convection
MODULE 4-6 Heat Transfer by Radiation
MODULE 4-7 Change of Phase - Boiling
MODULE 4-8 Burnout and Flow Instability
MODULE 4-9 Reactor Heat Transfer Limits

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Because heat is energy and not a substance, the transfer of heat from place to place is called heat flow. Module 4-4 described "Heat Flow by Conduction." This module presents another kind of flow: "Heat Flow by Convection."

In the convection mode, heat is transmitted by mass motion of a heated fluid. For example, consider the fan on a space heater in a large room (Figure 4-5-1). Hot air

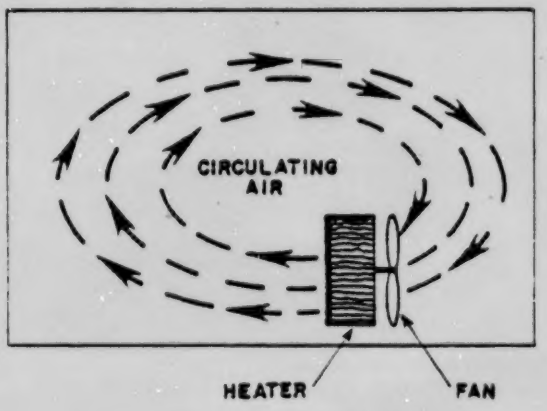


Figure 4-5-1. Warm air forced out of space heater by fan mixes with and warms cold air by convection.

is moved from the vicinity of the heat source to the area to be heated. Similarly when forced convection is used to transfer heat in a power plant, the heated fluid is moved (pumped) to a turbine, heat exchanger or other device.

In gases and liquids, convection currents often result from variations in density, caused by temperature changes. For instance, hot air, which is less dense than cold air, rises from above a radiator and strikes the ceiling, spreading throughout the room. This motion is due to the pres-

sure exerted by the cooler and denser air, which flows toward the bottom of the room.

MODULE PREREQUISITES

To understand this module, the student should have a working knowledge of basic physics and high-school algebra and should have completed Module 4-4, "Heat Flow by Conduction."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Write the equation for forced convection, define its terms and give its significance.
2. Discuss applicability and limitations of the forced convection equation.
3. Explain the physical phenomena of natural convection.
4. Compare forced and natural convection as useful heat transfer mechanisms.
5. Determine the convection currents produced by the expansion of fluids in a confined area.

HEAT TRANSFER RESISTANCE

As stated previously, transfer of heat by mixing of the hot and cold bodies is called convection. This mechanism, of course, is generally limited to heat transfer in fluids (liquids or gases). When good mixing exists, the resistance to heat transfer is very low. Thus, when it is desirable to promote rapid heat transfer, devices that promote convection are employed to the maximum extent practical.

In a reactor, such devices include high coolant velocities (to minimize stagnant areas and promote turbulence), mixing vanes and nucleate boiling.

Heat transfer in fluids is practically never a pure convective process. This statement especially applies in the case of a fluid flowing past a metallic surface, as in a reactor core (and in most heat exchangers). Fluids have a tendency to adhere to solid surfaces (Figure 4-5-2), which can result in the formation of a virtually stagnant film on the surface. Although this film is ordinarily very thin, heat transfer through it is mainly by conduction rather than convection, and its presence can markedly increase the overall heat transfer resistance of the fluid (Figure 4-5-3). Thus, to evaluate the resistance of a material in which convection plays a part, a number of parameters must be known; for example, flow rate, flow geometry and fluid temperature (which strongly influences its viscosity and, in turn, influences its susceptability to formation of films on surfaces), thermal conductivity and steam content. A significant resistance occurs in the water film at the

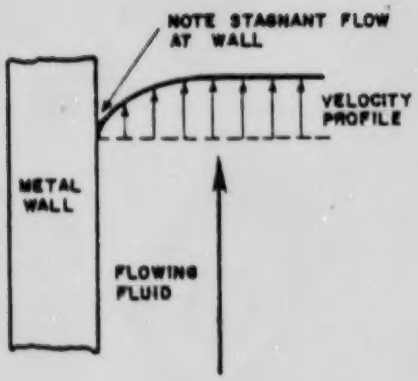


Figure 4-5-2.
Velocity profile of flowing fluid near metal surface or wall.

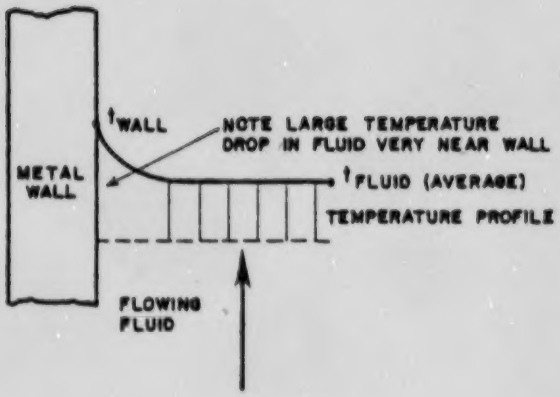


Figure 4-5-3.
Temperature profile of flowing fluid near metal surface or wall.

surface of the cladding. As a result, there is a measurable temperature drop as the heat passes through this film (Figure 4-5-4). Once the heat penetrates the film, it is transferred rapidly throughout the remainder of the water; resistance is so low that there is virtually no temperature variation throuthout the bulk of the coolant at any given elevation along the fuel rod. (Temperature of coolant increases steadily as it progresses upward along rod because of continual addition of heat to coolant.)

In gas space (helium) surrounding fuel pellet, heat transfer is by both conduction and convection, with conduc-

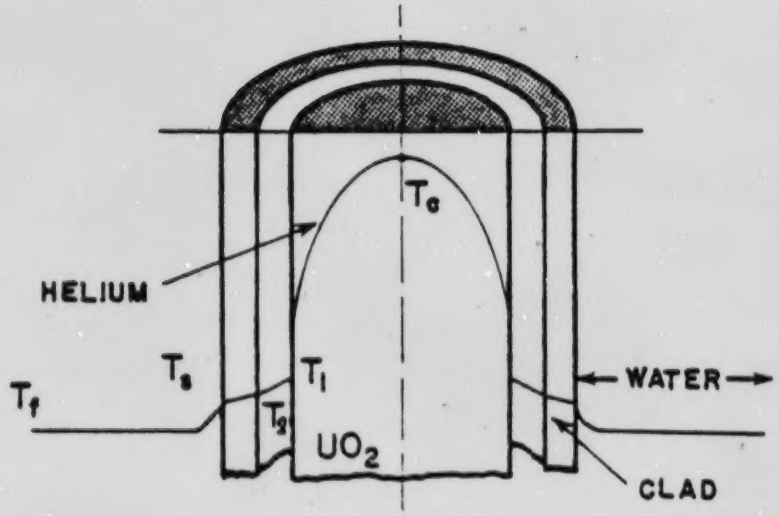


Figure 4-5-4. Cross section of a typical fuel rod, showing fuel center temperature (T_c), fuel surface temperature (T_1), temperature of interior cladding surface (T_2), cladding exterior surface temperature (T_s), and bulk fluid temperature (T_f).

tion playing an important part because the gas is relatively stagnant. Although thermal conductivities of gases are very low, and convection currents in the gas space are small, resistance to heat transfer remains relatively low due to the thin, annular shape of the space.

Some low-power nuclear pool reactors operate without pumping on this same principle; for example, the coolant near the fuel elements is heated by conduction and, as it rises, cooler liquid replaces it, maintaining circulation by convection.

NATURAL CONVECTION

Circulation set up by difference in temperature of a fluid and surface with which it is in contact is called natural convection. When fluid is a liquid, most of the heat removed from the hot surface is carried away by convection currents. Convection and radiation transfer heat from surfaces when fluid is a gas. Land and sea breezes and trade winds are examples of natural convection.

LAND AND SEA BREEZES

For several reasons, water in oceans heats more slowly than land along the shore. It has a higher specific heat than the land; it is transparent, allowing the sun's heat rays to penetrate to greater depth; and it is in more or less constant motion. Hence, by the middle of the forenoon on a sunny day, the land area, and also the air above such an area, will be more highly heated.

Colder, heavier air from the ocean blows in and forces the lighter air upward. Along the coast, a sea breeze comes up in the middle of the forenoon and blows steadily until late evening (Figure 4-5-5). At night, the land cools more

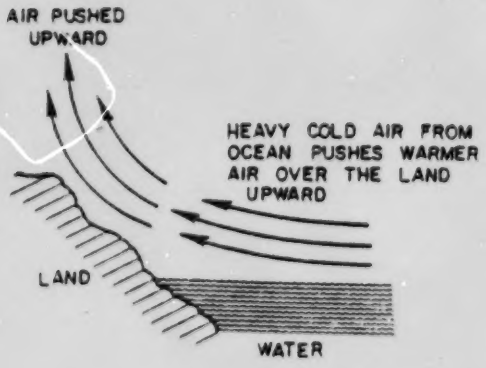


Figure 4-5-5.
Sea breezes blow toward land during day.

quickly than the water, and the air over the ocean becomes warmer than it is over the land. A land breeze then flows toward the ocean, usually beginning shortly before midnight. Fishermen along the coast use land breeze to go to sea at night; they return in the forenoon with the sea breeze (Figure 4-5-6).

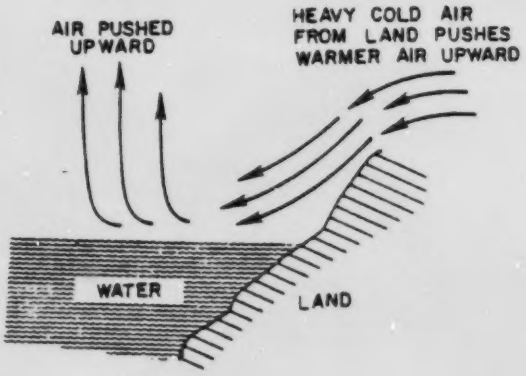


Figure 4-5-6.
Land breezes.

FORCED CONVECTION

Practically all nuclear reactors are cooled by "forced convection;" convection may be laminar (streamlined) or turbulent. In laminar flow, energy is lost by the drag of one layer of fluid against another. In turbulent flow, fluid elements move radially as well as axially. The combination of these components increases activity within the fluid by eddy current motion of the fluid. This results in a large increase in heat transfer as compared to laminar flow. Forced convection is therefore mainly turbulent in nature. These eddy currents occur mainly in the central part of the flow pattern (Figure 4-5-7), with predominantly laminar

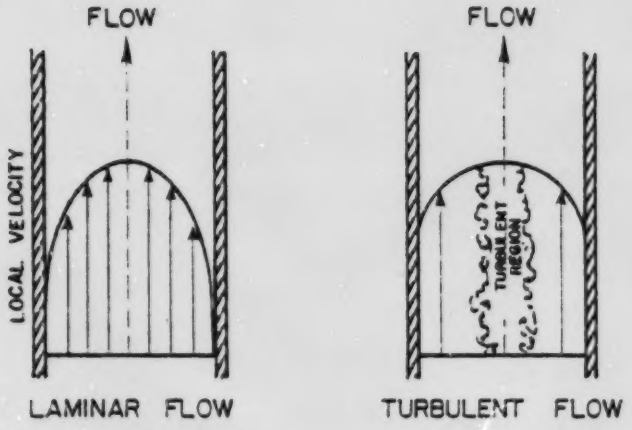


Figure 4-5-7. Velocity profiles of convection for laminar flow and turbulent flow.

flow near the wall and most of the resistance to heat transfer in this area. The basic formula for convective heat transfer from a heated surface to a flowing surface may be written as follows:

$$q = hA\Delta t \qquad \text{Equation 4-5-1 (Equation = Eq.)}$$

where

q = heat transfer rate, Btu/hr.

A = area of surface, sq ft.

h = coefficient of convective heat transfer, Btu/hr-ft^2-°F.

Δt = temperature difference, °F = $t_{wall} - t_{fluid}$ (Figure 4-5-3).

Equation 4-5-1 may also be written as follows:

$$q = \frac{\Delta t}{R_C}, \text{ where } R_C = \frac{1}{hA}$$

where

R_C = resistance to convective heat transfer.

As stated in the previous module on conductive heat transfer:

$$R = R_C + R_h$$

where $R_h = \frac{\ell}{k_h A}$ or conductive transfer.

Also,

$$R = \frac{1}{hA} + \frac{\ell}{k_h A}$$

$$RA = \frac{1}{h} + \frac{\ell}{k_h}$$

= the combined effects of convective and conductive resistance to the flow of heat.

If a quantity, designated as U, is defined so that:

$\frac{1}{U} = \frac{1}{h} + \frac{\ell}{k_h}$ or the overall coefficient of heat transfer; then, $R = \frac{1}{UA}$, and the net rate of heat flow due to conductive and convective elements is

$$H = \frac{\Delta t}{R} = UA\Delta t.$$

EXAMPLE

Find the required surface area when a heat load of 30,000 Btu/hr is to be moved across a temperature difference of 30°F, and the overall coefficient of heat transfer is 100 Btu/hr-ft^2-°F.

Solution:

$$A = \frac{q}{U\Delta t}$$

$$= \frac{30,000}{100 \times 30}$$

$$= 10 \text{ ft}^2.$$

It should be noted that the overall coefficient of heat transfer, U, is a very complex quantity, as can be seen in the following simple example.

EXAMPLE

Figure 4-5-8 is an illustration of heat transfer

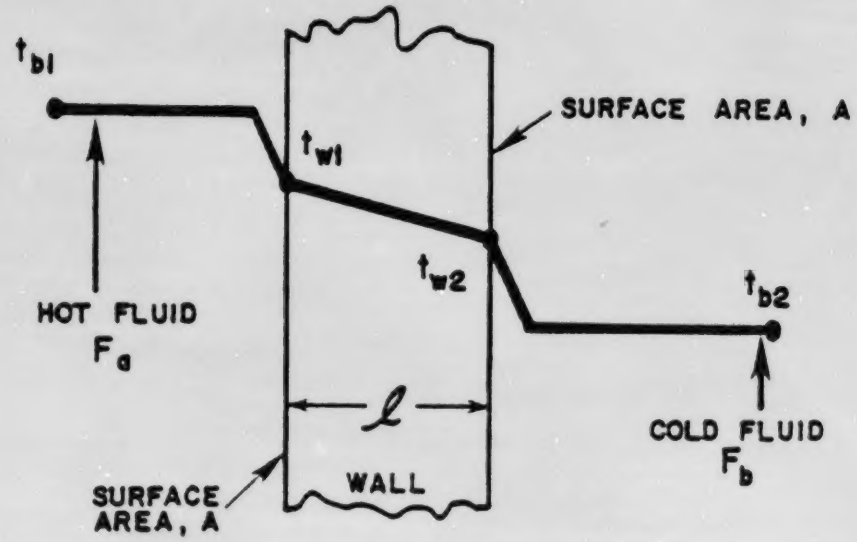


Figure 4-5-8. Heat transfer across a plate.

from one fluid, across a plate from a F_a, through a plate of thickness ℓ with a conductivity k_h to a second fluid F_b, the heat crosses two surfaces each with an area A, and two coefficients of convective heat transfer, h and h_2.

$$\text{Total resistance } R = \frac{1}{h_1 A} + \frac{\ell}{k_h A} + \frac{1}{h_2 A}$$

and

$$\frac{1}{U} = \frac{1}{h_1} + \frac{\ell}{k_h} + \frac{1}{h_2}.$$

Steam and internal-combustion engines utilize the principles of convection for operation. Convection currents help to supply air to burn the fuel in the firebox of a steam engine. Water is circulated from the boiler through the water tubes in the firebox by convection currents. Heat reaches the water tubes and bottom of the boiler from the flame by convection.

In the internal-combustion engine, the water-cooling system is most commonly used. In this system there are two general methods of circulating the water through the jackets surrounding the cylinders. One depends upon convection currents set up by the warm water rising and the cool water sinking. This is known as the thermosyphon method. The second method most commonly used for circulating the water is the forced or pump method. In both methods, as the water circulates around the cylinder walls, it gains heat by conduction and carries it, either by convection currents or by pump, as forced convection to the radiator.

EXERCISES

1. Why does dew or frost seldom form on a cloudy night?
2. The transfer of heat from a reactor by forced convection results in loss of power. Where does this loss come from?
3. What two forms of heat transfer are relatively unimportant in a nuclear reactor?
4. Forced convection can be either laminar or turbulent. Describe each type and draw a sketch illustrating each.

MATERIALS

1 250 cc flask.
1 two-holed rubber stopper to fit flask.
1 set glass tubing.
1 burner or hot plate.
1 ring stand or tripod.
1 potassium permanganate solution - 1/2%.
1 battery jar (8 in or 10 in).
1 thermocouple or glass-bulb thermometer.

PROCEDURES

1. Fill small flask almost to top with potassium permanganate solution; heat solution to about 60°C. Note any expansion during heating. Close flask with rubber stopper, which carries two pieces of glass tubing - one extending almost to bottom of flask and the other long enough to reach almost to surface of water as shown in Figure 4-5-9. Lower flask into battery jar,

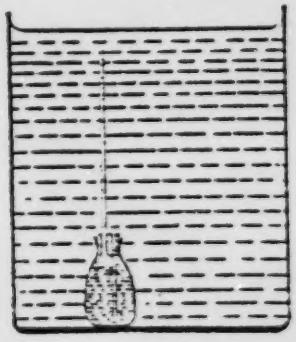


Figure 4-5-9.
Procedures apparatus.

which should be almost full of water. Make a sketch of apparatus and convection currents that are set up.

How was heat transmitted from flame to water in flask in beginning of experiment?

Make a list of practical applications of convection currents.

2. Place one-gallon (approximate) pan of water on hot plate.

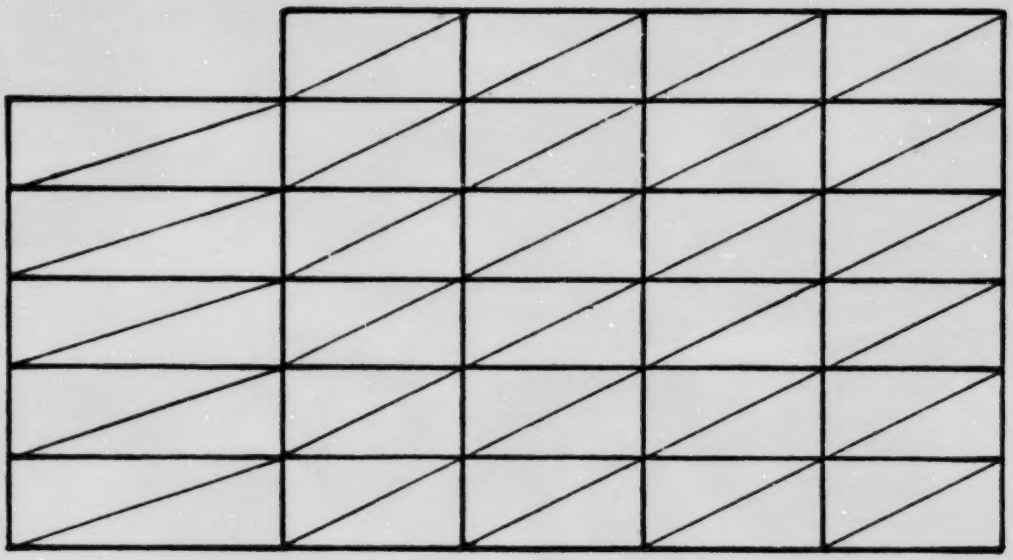
Heat water until bubbles just begin to form. Adjust heat at this condition; allow temperatures to stabilize for 15 minutes.

With thermocouple or glass-bulb thermometer, take temperatures within water at 1-inch spacings along a 2-dimensional vertical/axial plane.

Record results on Data Table 4-5-1; plot on graph paper.

Discuss results. Are they as expected? Where are highest readings? Why? Where are lowest readings? Why?

DATA TABLE 4-5-1



Note: Divide pan into horizontal grid with 2-inch spacing in both directions. Take temperatures from each grid area, at depths A and B. Record temperature readings in appropriate spaces on Data Table.

REFERENCE MATERIALS

Holman, J.P. Heat Transfer. 4th ed. New York: McGraw-Hill Book Co., 1976.

_____. Thermodynamics. 2nd ed. New York: McGraw-Hill Book Co., 1974.

Perry, J.H. Chemical Engineer's Handbook. 4th ed. New York: McGraw-Hill Book Co., 1977.

1. a. Write the equation for forced convection:

b. Define each term of the equation:

c. State the significance of the equation:

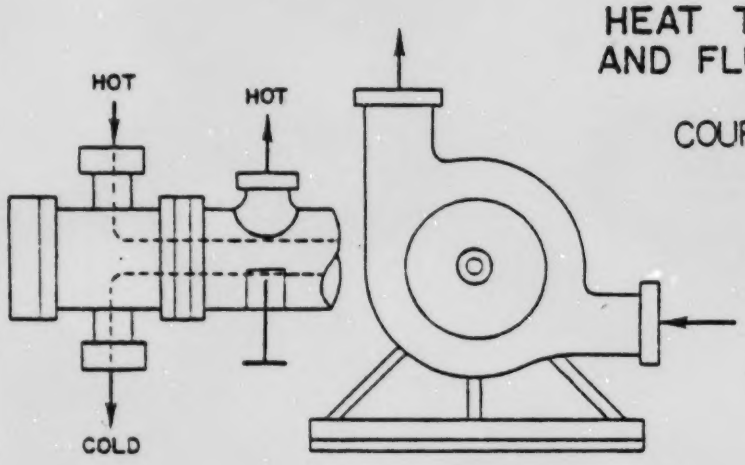
2. Discuss applicability and limitations of forced convection equation.

3. Explain the physical phenomena of natural convection.

4. Compare forced and natural convection as useful heat transfer mechanisms.

NUCLEAR TECHNOLOGY

MODULE 4-6 HEAT TRANSFER BY RADIATION



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

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COURSE 4 HEAT TRANSFER AND FLUID FLOW

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MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

Preceding modules have shown how conduction and convection heat transfer may be calculated. We now wish to consider the third mode of heat transfer, thermal radiation. Thermal radiation is that electromagnetic radiation emitted by a body as the result of its temperature.

We shall discuss the nature of radiation, transfer of radiation through space and influence of materials and arrangement of materials on total energy exchanged.

MODULE PREREQUISITES

A working knowledge of basic physics and high-school algebra, and completion of the previous modules in this course is prerequisite.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the physical phenomena of thermal radiation and compare to other types of electromagnetic radiation.

2. Define the term "blackbody."
3. Describe general techniques used to measure thermal radiation.
4. Use polished and blackened cups; show relationship of radiation heat transfer to time.

Hold your hands over a fire. Quickly they are warmed by radiation. In the same manner our world is warmed by the sun. Absorption of such radiation energy produces heat in the absorbing medium, though substances easily penetrated by thermal radiation are little warmed by their passage.

When thermal radiation is incident upon an object, some of it is reflected, some may be transmitted through the object, and the rest is absorbed. Polished metals are the best reflectors known, but they are very poor absorbers of heat. A poor absorber of heat is also a poor radiator. A roughened teakettle absorbs heat more readily than a highly polished one; it also loses heat faster by radiation.

Color of a substance also affects its absorbing power. A black surface absorbs heat faster than a white one. Hence, light-colored garments are cooler in summer sunshine than are black ones. Lampblack, on the other hand, is the best absorber known, and it is also the best radiator.

Crookes' radiometer may be used to demonstrate these facts. It consists of a partially evacuated bulb in which is suspended a light aluminum wheel that has a set of vanes in its circumference (Figure 4-6-1). Each vane is polished

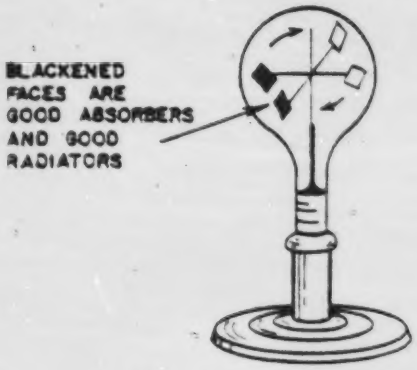

Figure 4-6-1. Crookes' radiometer operates in sunlight.

on one side and covered with lampblack on the other. When exposed to a source of radiant energy, heat is absorbed more rapidly by the black surfaces. The adjacent air is more highly heated and the molecules rebound with a greater velocity from the black surfaces, thus exerting greater pressure and causing the wheel to rotate in the direction of the black surfaces.

With Leslie's cube and a differential thermometer, it may also be shown that a black surface radiates heat faster than a white one (Figure 4-6-2). Surfaces of the

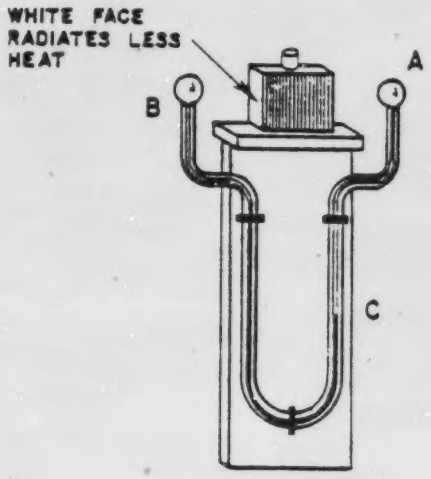

Figure 4-6-2.
Leslie's cube and a differential thermometer.

cube are painted different colors. The cube is filled with hot water and supported so that the black face is the same distance from bulb A of the thermometer as the white face is from bulb B. Since bulb A is heated more rapidly by radiation from the black surface, the air within this bulb expands more and forces the liquid C down the tube.

If you are sitting near a fireplace you receive more heat than someone who is farther away. The higher the tem-

perature of a radiator, the more heat waves it gives off by radiation. Measurements show that the intensity of radiant energy is directly proportional* to the temperature of the source, and inversely proportional to the square of the distance. The planet Mercury is only about one-third as far from the sun as the earth; hence it must receive about nine times as much radiant heat as the earth receives.

Radiant energy passes through some substances without heating them; for example, dry air is quite transparent to heat, but air containing much water vapor is much more opaque. Clouds absorb some heat as it travels from sun to earth. To some extent they also prevent loss of heat from the earth by radiation. On high mountains the sun's heat is intense due to lack of atmospheric interference (absorption).

Some substances, though transparent to light, are opaque to heat. Alum is an example. Conversely, iodine solution is opaque to light, but transparent to heat. Heat from the sun readily comes in through glass windows, but heat from the radiators does not pass out through glass readily. If the temperature of the source of heat is very high, the radiation is very penetrating. The heat waves given off from an absorber are much less penetrating. Glass is used for covering greenhouses and "cold frames;" the heat from the sun passes in through the glass, but there is little loss by radiation.

The essential thing is that every body radiates not just one type of radiation, but some of each. Consider two of the graphs (Figure 4-6-3). Curve (a) represents a white-

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* Actually, radiant energy is proportional to absolute temperature to the fourth power (A^4).

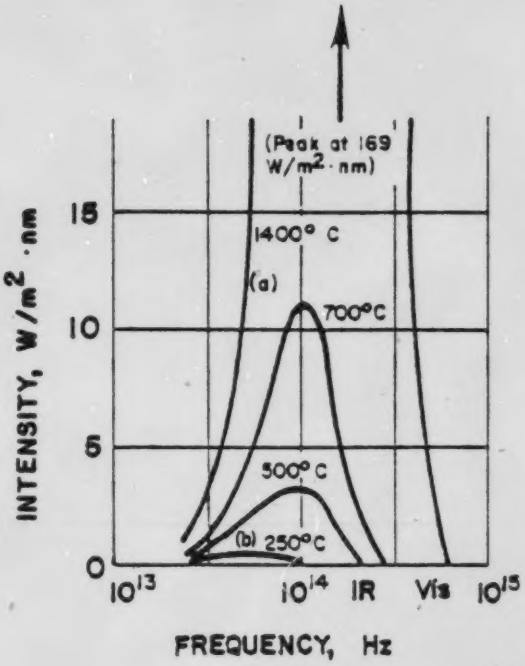


Figure 4-6-3.
Blackbody radiation at various temperatures.
(a) White-hot piece of coal at 1400°C; (b) blackberry pie at 250°C.

hot piece of coal in a fireplace, and it shows that the most intense radiation occurs in the infrared region. Some visible light and a small amount of ultraviolet (UV) radiation (too weak to be seen on the graph) also occurs. Also, a minute quantity of radiation appears in the radio band - the amount is relatively too small to cause TV interference.

When a pie (at 250°C) is set outdoors to cool, the total radiation is much less, and the character of the radiation is different (curve b). The peak radiation is now at about 5×10^{13} cycles (in the infrared region). And there are relatively more of the infrared and radio waves. Light from the pie is present, but far too weak to detect with the naked eye. The total radiation (all frequencies combined) is, of course, much less from the pie than from the glowing coal.

Radiation heat transfer requires no physical medium and is essentially electromagnetic in nature. Electromag-

netic waves of various higher frequency ranges are known by other names: heat, infrared radiation, visible light, ultraviolet radiation, x-rays and gamma rays. They all travel through a vacuum at 3×10^8 mi/s (186,000 mi/s). In solids the vibratory motion of electrically charged particles (ions) gives rise to electromagnetic radiation called "heat radiation" or "infrared radiation." The various electromagnetic radiations (Table 4-6-1) are characterized by a wide variety of mechanisms for production and receptions. All of these radiations have the same velocity.

TABLE 4-6-1
ELECTROMAGNETIC RADIATIONS

Type of Radiation	Usual Source	Usual Detector	Approximate Frequency Range, Hz (cycles/s)	Approximate Wavelength Range, Meters
Infrared radiation (heat	Hot bodies	Thermocouples Thermometers Skin	10^{11}-3.8×10^{14}	3×10^{-3}-8×10^{-7}
Visible light	Hot bodies Electric arcs	Eye Photocell Photographic plate	3.8×10^{14}-7.5×10^{14}	8×10^{-7}-4×10^{-7}
Ultraviolet radiation	Electric arcs	Photographic plate Photocell Geiger counter	7.5×10^{14}-3×10^{17}	4×10^{-7}-10^{-9}
X rays	Impact of electrons on target	Photographic plate Geiger counter Ionization chamber	3×10^{17}-3×10^{19}	10^{-9}-10^{-11}
Gamma rays	Radioactive nuclei	Geiger counter Ionization chamber	$> 3 \times 10^{19}$	$< 10^{-11}$

The only way heat energy can traverse a vacuum is by electromagnetic radiation. In fact, "empty" space between the stars is crisscrossed by many electromagnetic radiations, and it has been estimated that 4×10^{-14} J of radiant energy is contained in each cubic meter of "empty" space (on the average).

Practically all the radiation received by the earth comes from the sun; at a place where the sun is directly overhead, 8.13 J (1.94 cal) would reach each square centimeter of the earth's surface every minute if the atmosphere were perfectly transparent. This has been going on for several billion years; why, then, has the earth's temperature not increased to some fantastic figure? The answer lies in radiation from the earth to surrounding space. The earth has become just hot enough so that daily loss of heat by radiation (which depends on the earth's temperature) just balances daily gain in energy from the sun. The sun itself is a gigantic fusion reactor continually converting rest mass into energy. Most of the radiation from the sun does not reach the earth, but passes on out into space.

Not all surfaces are equally effective in emitting or absorbing radiation, even though their temperatures are the same (Table 4-6-2). A white or shiny body is a poor absorber of radiation, since some of the incoming energy is reflected back away from the interior. By the same token, a white or shiny body is a poor emitter of radiation, since radiant energy within the body is reflected back. The surface looks shiny from the inside as well as from the outside! A perfect absorber is called a <u>blackbody</u>, and such a body absorbs all radiations, not merely visible light. A blackbody is also a perfect emitter.

TABLE 4-6-2

THERMAL CONDUCTIVITY OF COMMON MATERIALS

Substance	Approximate Thermal Conductivity K, $cal \cdot CM/cm^2 \cdot s \cdot C^\circ$
Masonite	0.00011
White pine	9.0002
Building brick	0.0015
Glass	0.0025
Concrete	0.002
Steel	0.11
Copper	0.92

It is evident that the same region that performs as a good absorber (when cool) also serves as a good emitter (when hot). According to these ideas, a living-room "radiator" should be painted black for efficient radiation of heat. A light-colored paint job may be decorative, but hardly in accord with the laws of physics. Most of the heat transfer from a "radiator" is by direct contact of air molecules with faster-moving iron atoms or paint molecules; such a process is conduction and does not depend greatly on the blackness of the surface.

At a given temperature, all blackbodies look much alike and emit the same distribution of frequencies of radiant energy. In a fireplace, the "red-hot" iron poker is almost indistinguishable from the "red-hot" carbon (coal or ash)

that is at the same temperature. The radiation pyrometer is a device to determine the temperature of a furnace by comparing the color of the contents with that of an electrically heated wire at a known temperature. To the extent to which all substances are "black," it is immaterial just what substance is in the furnace. The same radiation pyrometer can be used to measure the temperature of molten iron or molten glass.

EXERCISES

1. Is it economical to keep stoves highly polished? Explain.
2. Why is it necessary for a radiator to have more sections when used with hot water than with steam heat?
3. Do liquids cool more quickly in a tarnished pot or a highly polished one?
4. Why is silvered glass used in making thermos bottles?
5. Two pieces of cloth are laid on the snow; one is black, the other white. The black one sinks into the snow faster on a sunny day. Why? If the black one is covered with powdered alum and the white one with powdered iodine, the condition will be reversed. Explain.
6. How does heat get from a radiator to various parts of a house?

MATERIALS

1 beaker, 1000 cm^2.
2 beakers, 250 cm^2.
1 bright metal cup.
1 bright metal cup coated on outside with lampblack.
2 thermometers.
1 ring stand.
1 wire gage.
1 burner.
1 thermos bottle.
1 watch.

PROCEDURES

Warm or hot objects radiate heat to the surrounding medium. The rate at which heat is radiated depends upon the color of the radiator and upon the nature of its surfaces.

Fill a large beaker (1000 cm^2) with water and heat it to 80°C. With this hot water, fill each of the 250-cm^2 beakers; quickly transfer the water from each to a cup (250 cm^2 in each cup). At two-minute intervals, take thermometer readings for the polished cup as well as the blackened cup. Also, from the beaker, pour 250 cm^2 of the hot water into the thermos bottle and take thermometer readings at ten-minute intervals. Record readings on Data Table 4-6-1.

Continue in this manner until six or eight readings have been taken. Room temperature should also be recorded.

DATA TABLE

DATA TABLE 4-6-1

Time	Polished Cup Temp.	Black Cup Temp.	Room Temp.	Polished Cup Temp. Minus Room Temp.	Black Cup Temp. Minus Room Temp.
1					
2					
3					
4					
5					
6					
7					
8					

REFERENCE MATERIALS

None.

1. Define "thermal radiation."

2. Explain the physical phenomena of thermal radiation.

3. How may thermal radiation be measured?

4. Which absorbs heat more readily (check one):

   A black surface? _____

   A white surface? _____

5. Name the best known heat absorber.

6. Which absorbs heat more readily (check one):

   A roughened teakettle? _____

   A polished teakettle? _____

7. Does radiation from the sun lose more heat when passing through a relatively dry cloud or a relatively wet one?

   Why?

8. Do all bodies radiate?

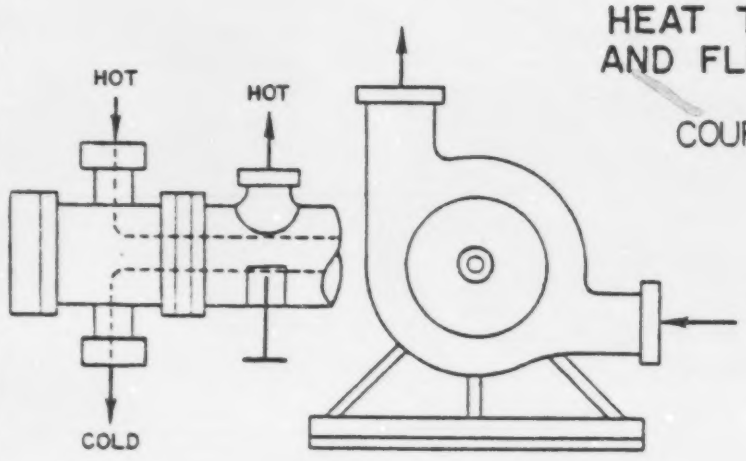
9. Can heat traverse (pass through) a vacuum?

   If so, how?

10. How does a radiation pyrometer measure the temperature of a body?

NUCLEAR TECHNOLOGY

MODULE 4-7 CHANGE OF PHASE - BOILING



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiation

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

Thermodynamics, as a science, deals with energy changes into transient forms (heat and work).

A consideration in the design of some heat transfer systems is developing reliable information on steam properties. Properties of steam and water are found in the "1967 ASME Steam Tables," and information used in this text comes from this source.

Water, steam and superheated steam, at any given combination of pressure and temperature, have identifiable properties of specific volume, specific heat content and total heat content. These properties, also given in the Steam Tables, allow the student to relate heat transfer to work done.

MODULE PREREQUISITES

The student should have completed a physics course, high school mathematics through algebra (including an ability to solve equations) and all previous modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe physical process that occurs as liquid becomes steam.
2. Define void fraction and quality.
3. Define nucleate, bulk and film boiling.
4. Perform experiments that show boiling point variations with pressure changes.

BASIC CONCEPTS

Matter exists in three basic states:

Solid.
Liquid.
Gas.

A solid has a definite volume and a definite shape. A liquid has a definite volume and takes the shape of the vessel that contains it. Gases have neither a definite volume nor shape.

A gas takes the shape and volume of the container that holds it, and it changes with any change in either the volume or shape of that container. Steam is water in a gaseous form.

The process that describes the change of water (liquid) to steam (gas) is called boiling. Water can exist as a liquid or gas over a wide range of temperatures and pressures; however, for any pressure there is a temperature at which water boils and becomes steam, and for any temperature there is a pressure at which water boils and becomes steam. This temperature-pressure relationship is called "saturation."

Below saturation temperature, at a given pressure, water exists as water. Above saturation temperature, at a given pressure, water exists either as steam or water, depending on its heat content. In fact, at saturation temperature water is usually a two-phase (water and steam mixture).

For a given set of conditions water or steam has a given set of properties:

Specific volume.
Total heat content.
Specific heat content.

THERMODYNAMIC PROPERTIES OF STEAM AND WATER

Specific volume, the relationship of volume and mass, is expressed as cubic feet per pound, or cubic meters per gram. The standard notation for volume is "v." For a given pressure-temperature relationship there is a definite volume for water or steam. At saturation temperature-pressure, the two-phase mixture of steam has a volume/mass relationship dependent upon the ratio of steam to water.

Enthalpy, sometimes called "heat content," the relationship of heat and mass, is expressed in Btu's per pound, or calories per gram. The standard notation for enthalpy is "h." For a given pressure-temperature relationship, each pound of water contains a specific amount of heat.

Entropy, the relationship of heat content, mass and absolute temperature, is expressed as Btu's per pound per degree Fahrenheit, or calories per gram per degree Centigrade. The standard notation for entropy is "s." Entropy, a distribution property or factor complementing the intensity factor of temperature is complex - beyond the scope of this discussion.

Latent heat of vaporization is the amount of heat that can be added to water at the saturated temperature-pressure condition without increasing water temperature. No observable temperature increase occurs until all water has been

converted to steam. The term that describes this heat is "latent (hidden) heat of vaporization."

QUALITY AND VOID FRACTION

Quality is defined as the fraction of vapor in a liquid vapor mixture:

$$\text{Quality} = \frac{M_v}{M_v + M_\ell}$$

where

M_v = vapor mass.
M_ℓ = liquid mass.

When multiplied by 100, this value is expressed as "percent quality."

As heat is added to a liquid, saturation enthalpy is reached. When additional heat is added, a portion of the liquid vaporizes and quality increases until sufficient heat has been added to boil all the water to steam (100% quality).

Void fraction is defined as the percentage of flow area occupied by steam (compared with total flow area):

$$\text{Void fraction} = \frac{A_v}{A_v + A_\ell}$$

where

A_v = vapor area.

A_ℓ = liquid area.

When multiplied by 100, void fraction is expressed as "percent void."

Assuming a homogeneous flow, void fraction can be calculated (based on pressure, steam quality and specific volumes of saturated steam and water - found in Steam Tables).

FRICTIONAL LOSS

Frictional losses caused by surface roughness are related to the channel. The sum of these account for pressure drop in a flow channel.

TYPES OF BOILING

When water is heated in an open pot, bubbles of water vapor form on the heated surface. This vaporization is called boiling. As these bubbles rise through the cooler layers of liquid they collapse. When the entire liquid is hot enough, these bubbles reach the surface freely. At this point, vaporization occurs throughout the liquid.

The "boiling point" is the temperature-pressure relation at which boiling takes place. (A liquid does not get any hotter as it continues to boil. Water has the same temperature when boiling slowly or vigorously.)

Four types of boiling are of interest in nuclear reactors:

Subcooled boiling.
Nucleate boiling.
Film boiling.
Bulk boiling.

It is customary to represent the types of boiling on a heat flux (Btu/hr-ft^2) versus temperature difference curve (Figure 4-7-1). The temperature difference is that between the surface temperature and the average (bulk) fluid temperature. Actual values of heat flux and temperature differences depend upon surface geometry, fluid velocity, type of fluid and pressure.

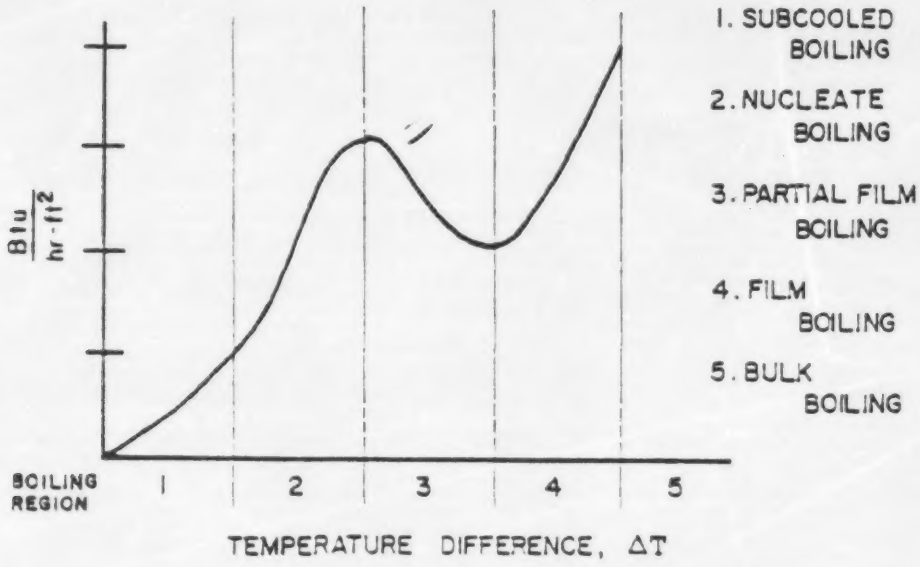


Figure 4-7-1. Heat flux versus temperature difference.

SUBCOOLED BOILING

In the region of subcooled boiling, superheated liquid transfers heat by pure convection. When water is boiled in an open pot, convection currents can be seen as apparent waves or lines of water. The superheated liquid rises to the surface and evaporates, or mixes with the bulk liquid and becomes subcooled. At this point, the heat transfer rate per unit area is almost a linear function of the difference in temperature between the heated surface and the liquid.

NUCLEATE BOILING

As the rate of heating increases, small bubbles form on the heated surface, break away and are collapsed in the subcooled liquid. A small amount of vapor reaches the surface and is released. In this early stage of nucleate boiling, heat transfer rate per unit area increases somewhat faster in relationship to differential temperature than in the subcooled region.

As the heating rate increases, nucleate bubbles tend to rise to the surface and escape into the air. The heat transfer rate per unit surface area increases rapidly in this range as more and more bubbles form and break away.

PARTIAL FILM BOILING

As nucleate boiling bubbles start to grow in number and link together, they tend to disrupt flow of new water onto the heated surface (termed partial film boiling or transition boiling). This boiling is characterized by rapid changes in heat transfer rate per unit volume and differential surface temperature. (Transition boiling region is un-

stable and the condition persists only momentarily.)

FILM BOILING

As the heating rate increases further, bubbles form so rapidly they blanket the surface. This blanket prevents inflow of fresh liquid from taking its place. Heat must then be conducted through the film blanket before it can reach the liquid process. During film boiling, heat transfer rate per unit volume decreases and surface temperature increases rapidly, until differential temperature is great enough to cause increasing heat transfer through film layer.

BULK BOILING

During bulk boiling, surface temperature is so high the heat transfer rate is large enough to boil all water in the container.

EXERCISES

1. Describe boiling (and physical process that takes place when liquid becomes vapor).
2. Define quality; show mathematically how liquid and vapor phases of a two-phase mixture are related.
3. Define void fraction; show mathematically how liquid and vapor phases are related.

4. Discuss things that affect pressure drop in a flow channel.
5. Discuss subcooled, nucleate, partial film, film boiling and bulk boiling; describe each; for each, relate heat transfer rate and differential temperature.
6. From Steam Tables, determine v, n and s for water and steam in the following conditions:

   212°F, 14.7 psia.
   600°F, 400 psi.
   400°F, 600 psi.

   Indicate which is water and which is steam.

MATERIALS

1 steam generator.
1 manometer tube with mercury.
1 Bunsen burner.
1 thermometer.
1 length of rubber tubing for condenser.
1 500-cm^3 flask.
2 ring stands.
2 iron clamps.
1 quantity of table salt.
1 gallon denatured alcohol.
1 solid rubber stopper to fit 500-cm^3 flask.
1 beaker.
1 vacuum pump

1 pinch clamp.
1 distilling flask.
1 condenser.

PROCEDURES

1. Set up steam generator as shown in Figure 4-7-2.

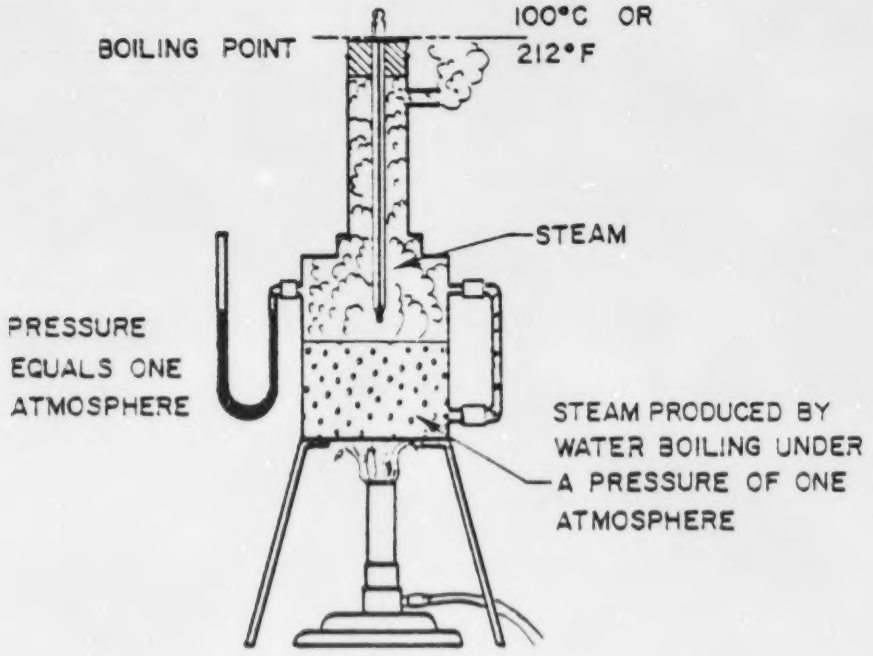


Figure 4-7-2. Experimental arrangement.

Slip a 2-inch length of rubber tubing onto outlet tube near top of chimney; press stopper (holding thermometer) firmly into top of chimney; heat water in generator to boiling; note temperature while water boils (for a few minutes); clamp side of chimney with pinch clamp (leave clamp on only a short time, else steam pressure may force mercury out of manometer tube or stopper out of chimney); note rise of mercury in manometer tube, read thermometer. Has boiling point changed with increase in pressure?

2. Fill 500-cm^3 flask half full of water; heat to boiling. Insert solid rubber stopper; invert flask and pour cold water on it. Observe water inside flask. Fill beaker half full of water at room temperature; insert thermometer; place beaker and thermometer under glass bell of a vacuum pump; start pump; after a few minutes, observe water and note temperature. Does reduction of air pressure affect boiling point of water?

3. Set up apparatus as shown in Figure 4-7-3. Dissolve

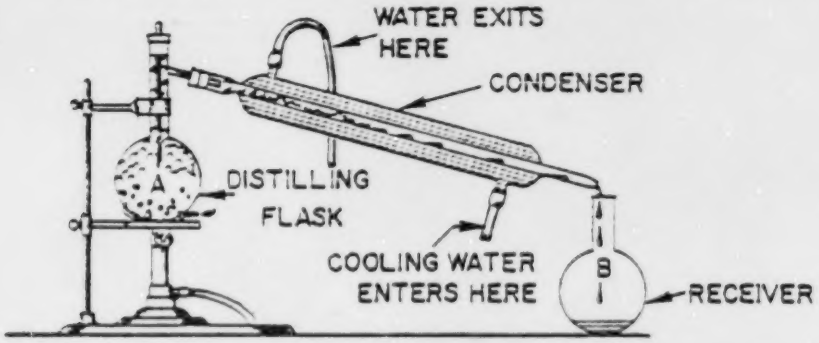


Figure 4-7-3. Experimental arrangement.

about 30 g of table salt in 100-cm^3 of water; pour solution into distilling flask "A;" heat until it has boiled

a few minutes; note temperature. How does boiling point of salt solution compare with that of pure water as determined in experiment 1? Taste distillate in "B." Does is contain salt?

Replace salt solution in "A" with solution of 25 cm^3 of alcohol in 25 cm^3 of water; boil for a few minutes; note boiling temperature. How does this temperature compare with that of pure water and with that of salt solution? Smell distillate in "B." Is it pure water?

DATA TABLE

None.

REFERENCE MATERIALS

Collier, J.G. Convective Boiling and Condensation. New York: McGraw-Hill, 1972.

1. Briefly describe physical process that occurs as liquid becomes steam:

2. Define:

   Void fraction.

   Quality.

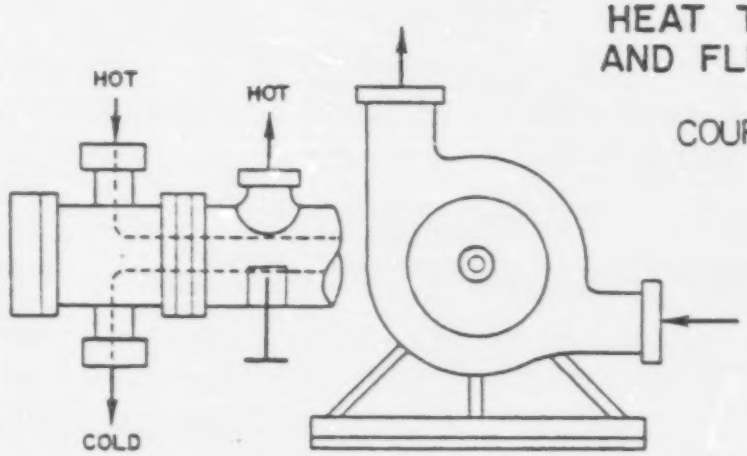
   Nucleate.

   Bulk.

   Film boiling.

NUCLEAR TECHNOLOGY

MODULE 4-8 BURNOUT AND FLOW INSTABILITY



HEAT TRANSFER
AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE MODULES

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiaticn

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

Heat transfer that takes place within a process is dependent upon temperature, pressure and heat flux (at the heat source surface). In a nuclear reactor, heat transfer takes place by conduction, convection and radiation.

Of the energy generated in the fuel (by fission), approximately 3% of it is transferred as heat to the coolant by radiation, and does not affect fuel or cladding temperature. The remaining 97% is transferred to the coolant, either by conduction through the fuel cladding or by convection from the cladding surface to the fluid.

This module examines these factors as they affect burnout and flow instability.

MODULE PREREQUISITES

The student should have completed high school algebra and physics, and all previous modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe burnout concept (DNB), give its significance and possible consequences, and list factors that affect it.
2. Describe flow instability, give its significance and possible consequences, and list factors that affect it.
3. Describe how burnout and flow instability are detected in actual reactor systems.
4. Draw a graph of surface temperature versus heat generation rate; show nucleate, transition and film boiling regions.
5. Determine necessary steps for preventing DNB and flow instability.

Heat flux is the rate of heat transferred through a unit surface for a unit time (Figure 4-8-1). Its dimensions

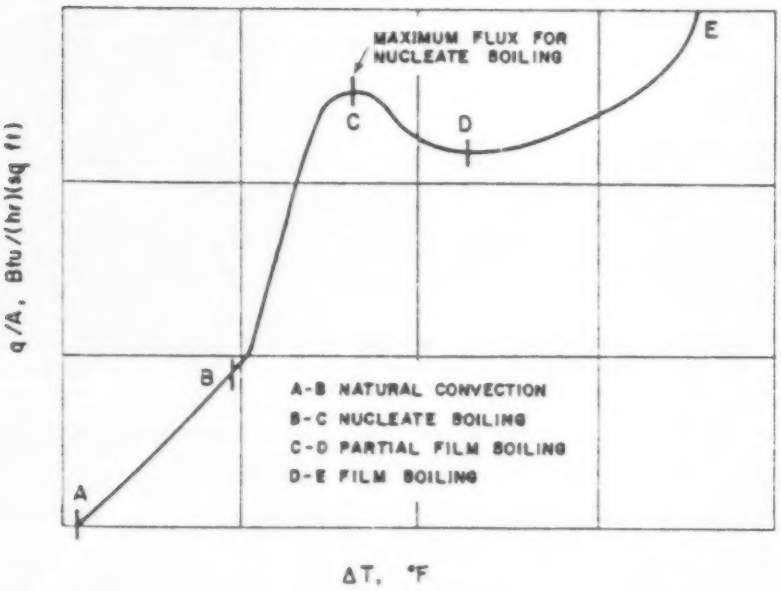


Figure 4-8-1. Typical types of boiling.

are given in Btu/ft^2-hr. Differential temperature refers to fuel surface temperature minus coolant temperature.

In the subcooled region, between A and B, heat transfer is mainly by conduction. The rate of heat generated is low enough that fuel cladding temperature is only slightly greater than that of the coolant. As rate of heat generation increases, surface temperature required to transfer increasing heat also increases (as a linear function of heat flux).

As heat generation increases further, heat flux reaches

a point at which individual boiling takes place on the surface of the fuel (point B).

Each bubble formed on the surface grows in size until it breaks away from the surface into the coolant. This convection heat transfer (Figure 4-8-2) is called nucleate boiling.

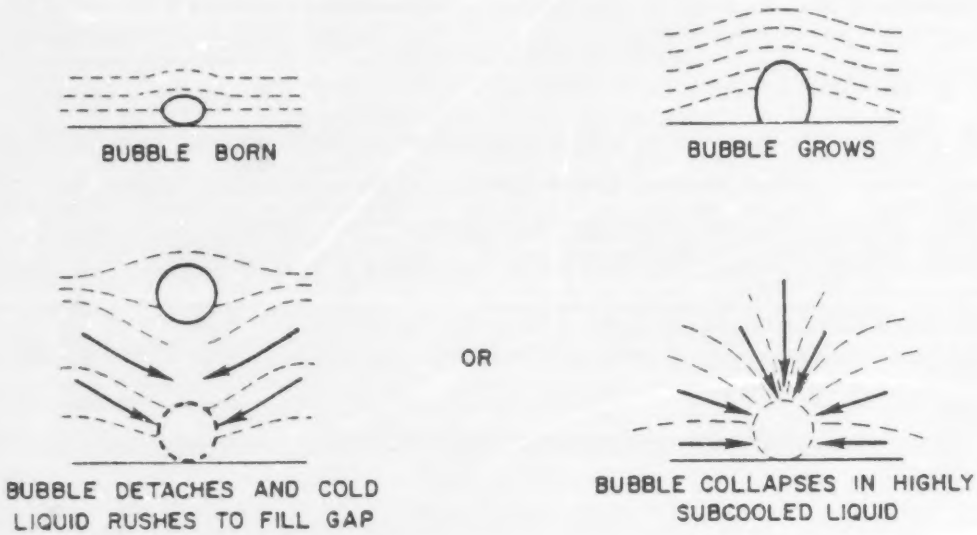

BUBBLE BORN
BUBBLE GROWS
BUBBLE DETACHES AND COLD LIQUID RUSHES TO FILL GAP
OR
BUBBLE COLLAPSES IN HIGHLY SUBCOOLED LIQUID

Figure 4-8-2. Nucleate boiling.

In nucleate boiling, the heat transfer rate increases much faster than the surface temperature because bubbles are continuously breaking away from the fuel surface and removing heat into the coolant.

As heat generation rate continues to increase, heat transfer rate increases further, with only a small increase in surface temperature. Finally, the rate of bubble generation is great enough to partially cover the surface. An effective insulation to heat transfer is formed. This point C (Figure 4-8-1) is the departure from nucleate boiling

(DNB); heat flux at this point is defined as critical.

Points C to D indicate the increase in surface temperature (with decrease in heat flux) as partial film boiling takes place. As fuel cladding temperature continues to increase, full film boiling is achieved (point D).

In full film boiling, the heat transfer rate again increases; however, film boiling usually takes place at temperatures above the melting point of the fuel cladding (or at temperatures so high that other mechanical properties of fuel cladding fail). This localized melting is called "burnout."

As heat flux reaches a critical point, heat transfer rate decreases and fuel cladding temperature increases rapidly to the burnout point, with no increase in heat production in the fuel. Therefore, it is necessary for the protection of the fuel cladding, to ensure that the reactor is operated with a heat flux below the critical heat flux during both normal and accident condition.

BURNOUT (DNB)

Normally, reactors are operated well below critical heat flux (burnout heat flux). Critical heat flux is established experimentally in critical heat flux test loops. Once this critical heat flux is established, DNBR can be determined for reactor operating condition.

DEPARTURE FROM NUCLEATE BOILING RATE (DNBR)

DNBR defines the relationship between reactor maximum operating heat flux and critical heat flux at any point along a fuel pin. At the lower end of the fuel pin (Figure 4-8-3) where heat generation is low, actual heat flux

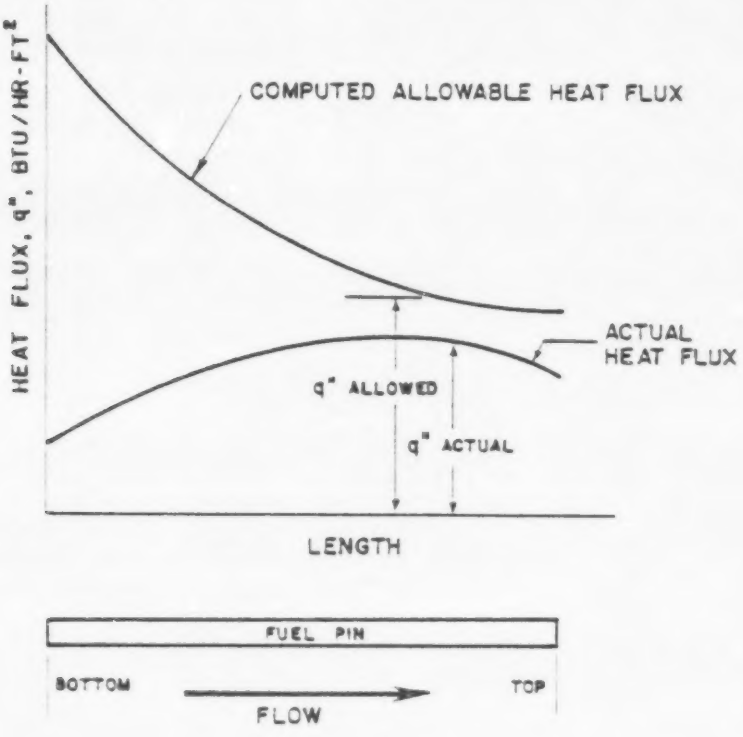


Figure 4-8-3. Actual and allowable heat fluxes along a fuel pin (typical).

is low, also. But allowable heat flux is high because coolant temperature is low and pressure is high; therefore, the DNBR is high.

As the coolant continues up the channel, temperature

increases, heat generation rate increases, and coolant pressure decreases; therefore, actual heat increases and allowable heat flux decreases, allowing DNBR to reach its minimum. Near the top of the core, coolant temperature is high, and coolant pressure is low; however, actual heat flux is low and DNBR returns to a higher value.

FACTORS THAT AFFECT DNB/BURNOUT

DNBR is not a measurable value; it can only be determined by measuring physical parameters of coolant (temperature, pressure, flow rate, and reactor power) and relating these values to critical heat flux, thereby establishing a DNBR minimum.

To understand how each of these factors affects DNBR, it must be understood how each influences actual heat flux and critical heat flux.

As DNBR decreases (Figure 4-8-4), all other system paraneters remain constant because of a decrease in critical heat flux and a corresponding decrease in flow.

As pressure in a reactor vessel decreases, with all other system parameters constant, DNBR decreases with pressures (Figure 4-8-5), caused by reduction in critical heat flux as pressure is reduced.

For a constant critical heat flux (Figure 4-8-6), DNBR decreases as actual heat flux increases (as a function of power).

The relationship between pressure and temperature at a typical minimum design DNBR (Figure 4-8-7) can be seen at normal temperature and pressure. The reactor operates with a DNBR much larger than this minimum design value.

The relationships between critical flux, actual sur-

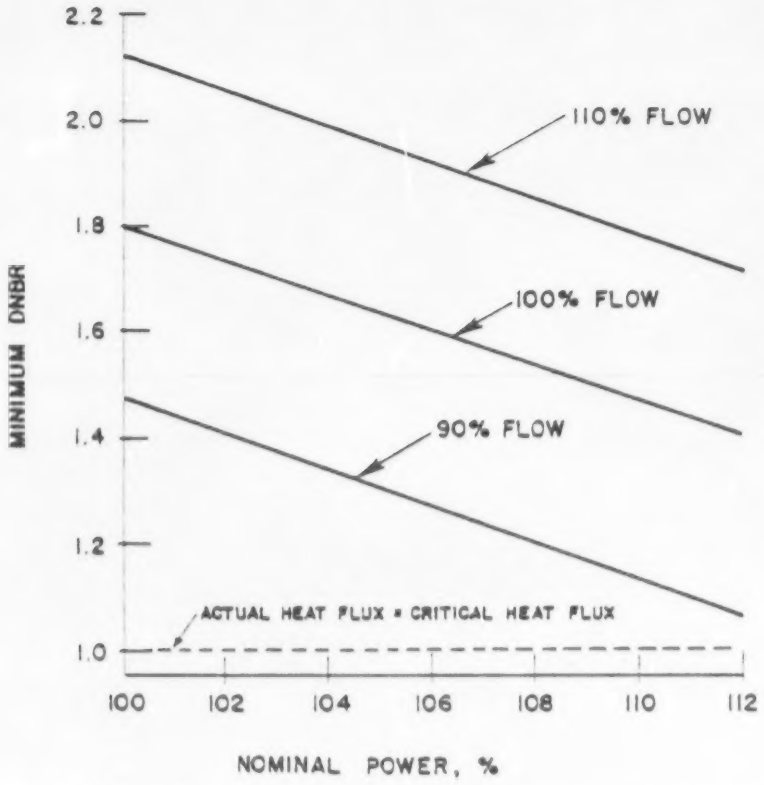


Figure 4-8-4. Effect of flow and power on minimum DNBR.

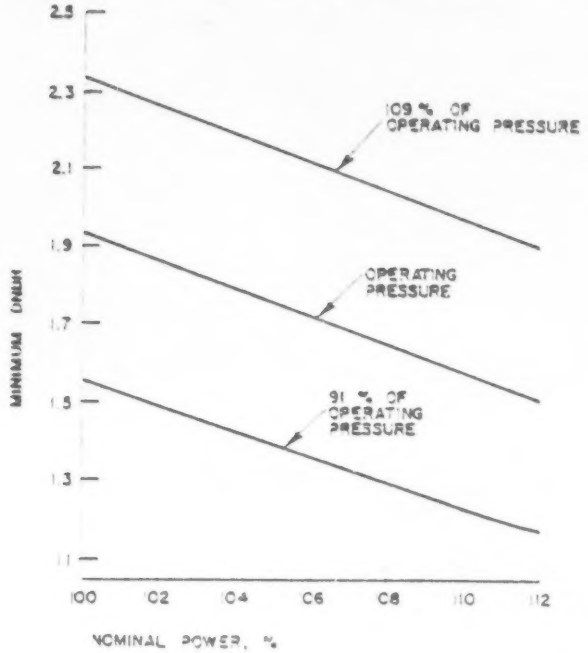


Figure 4-8-5. Effect of pressure on minimum DNBR.

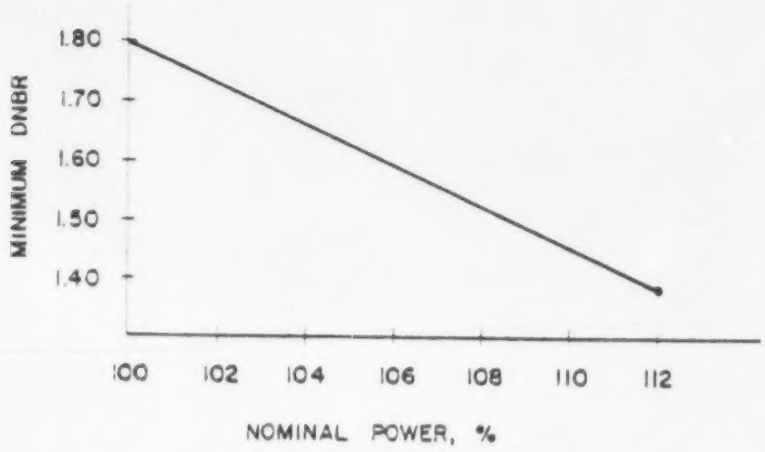


Figure 4-8-6. Effect of power on minimum DNBR.

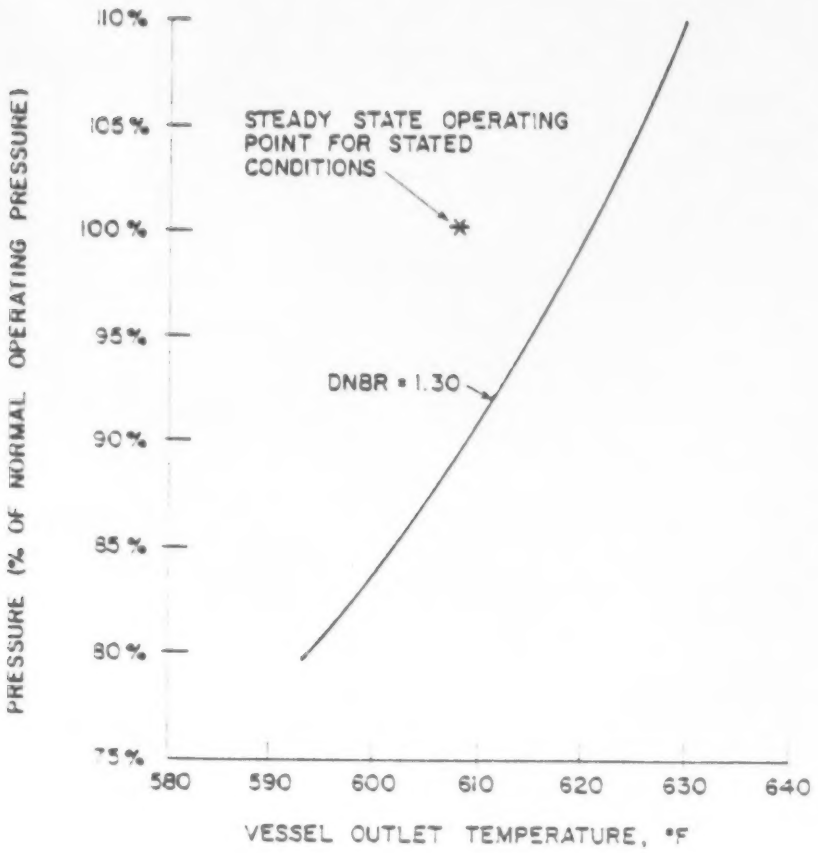


Figure 4-8-7. Relationship between pressure and temperature for constant DNBR (typical conditions).

face heat flux, and DNBR along the length of a typical fuel pin surface are shown (Figure 4-8-8) for the worst case channel. Minimum DNBR does not occur at maximum actual heat flux, but rather downstream because of a higher coolant temperature.

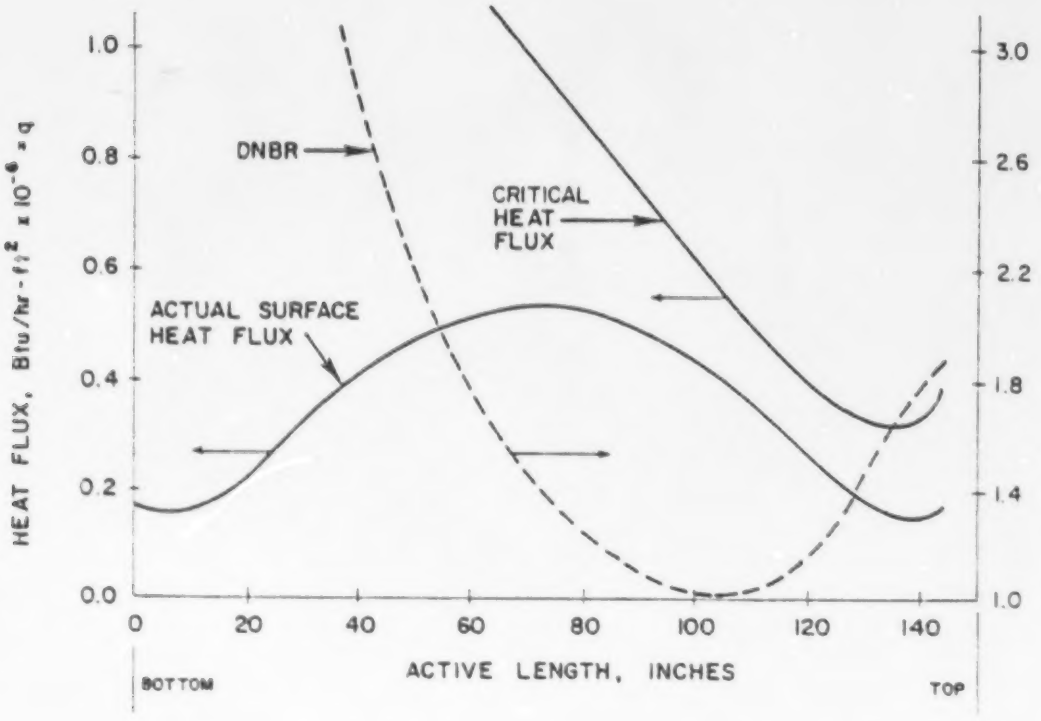


Figure 4-8-8. Critical heat flux, actual surface heat flux and DNBR (typical conditions).

QUALITY AS APPLIED TO WATER

In addition to DNBR limits, reactor design also considers water quality, which is defined as "weight percent of

steam in a steam-water mixture":

$$\text{i.e., quality} = \frac{\text{weight of vapor}}{\text{weight of vapor and weight of liquids}},$$

usually taken times 100 and expressed as percent. Maximum quality typically is limited to below 15%.

FLOW INSTABILITY

Before a fuel assembly is fabricated, a full-scale model is made and tested. Extensive testing ensures against flow instability.

During startup test programs of reactors using new fuel designs, an extensive first-of-a-kind test program is conducted. Results are compared with data taken from the reactor to verify flow stability.

REACTOR COOLANT FLOW AND BURNOUT

As illustrated previously, DNBR is affected by flow. The number of operating reactor coolant pumps determines reactor coolant flow rate, with only small differences produced by pump wear and coolant pump electrical power supply (frequency and voltage).

The relationship between DNBR and reactor power (Figure 4-8-9) differs with different pump combinations. For two-pump operations, the 15% quality limit is reached well before a DNBR of 1.3.

Minimum DNBR change occurs in the reactor for each

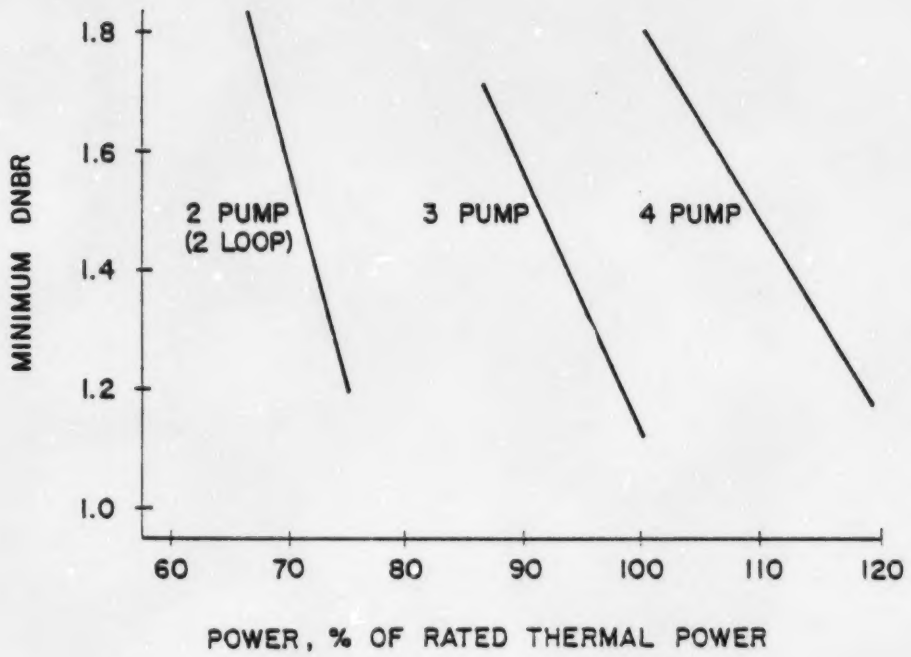


Figure 4-8-9. Minimum DNBR versus power for 2, 3 and 4 pumps operating in maximum design conditions.

reactor coolant pump trip. Minimum DNBR is reached in about 2.0 seconds after a pump trip (Figure 4-8-10).

DETECTION OF BURNOUT

Critical heat flux or burnout in itself cannot be detected directly; therefore, it is necessary to use measurable parameters to protect reactor fuel from burnout. The measurable parameters are power, temperature, pressure, and reactor coolant flow.

Protection system set points (Figure 4-8-11) provide protection against DNBR during reactor operation. Each

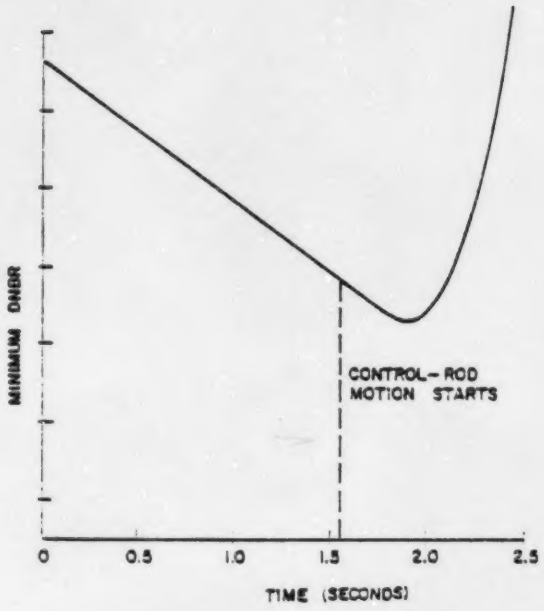


Figure 4-8-10. DNBR after coolant pump trip.

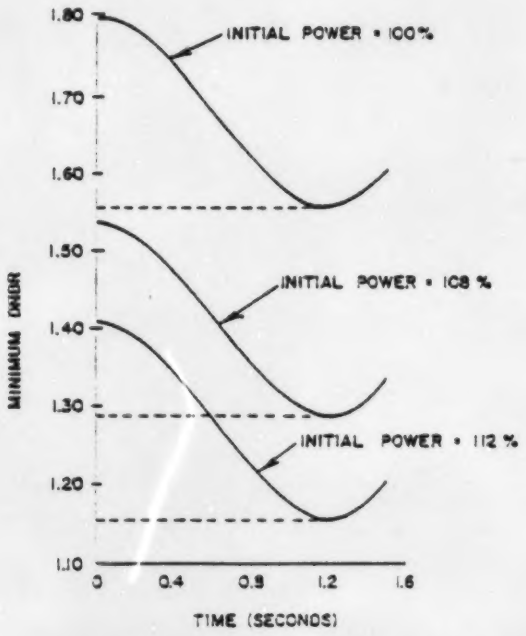


Figure 4-8-11. Protection system set points.

parameter is based on the most conservative operation of the reactor and includes penalties for instrument errors and delay times.

EXERCISES

None.

MATERIALS

Graph paper.
1 set (safety analysis report, technical specifications and operating procedures of an operating PWR nuclear plant).

PROCEDURES

1. Draw a graph of surface temperature versus heat generation rate; show nucleate, transition and film boiling regions.

2. List steps necessary to prevent DNB, based on data obtained from safety analysis report, technical specifications and operating procedures.
3. List minimum value(s) of DNBR for an operating PWR; give postulated incidents that could lead to a minimum DNBR.

DATA TABLE

None.

REFERENCE MATERIALS

El-Wakil, M.M. Nuclear Heat Transport. Scranton, PA: International, 1971.

Zweifel, Paul F. Reactor Physics. New York: McGraw-Hill, 1973.

1. Define critical heat flux:

2. Describe what takes place when critical heat flux is reached:

3. What is departure from nucleate boiling (DNB)?

4. Why is DNB called burnout?

5. Define departure from nucleate boiling ratio; discuss difference between DNB and DNBR:

6. A reactor is operating with a maximum heat flux of 1.04×10^5 Btu/ft^2-hr; critical heat flux is 10.3×10^5 Btu/ft^2-hr; fuel cladding surface area is 62,000 ft^2; peak-to-average ratio is 3:77.

   What is DNBR?

   What is average heat flux?

   What is thermal power level?

7. Discuss effect of each of the following on DNBR and critical heat flux:

   Reactor coolant pressure.

   Reactor coolant flow.

   Reactor temperature.

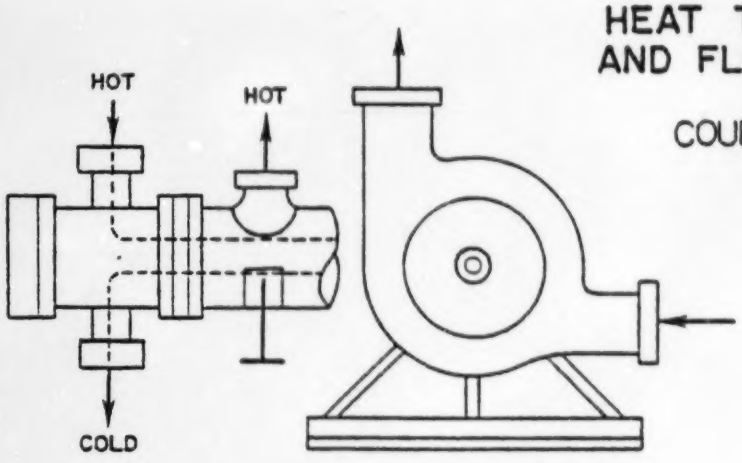
Reactor power.

Note: Assume that only one parameter changes (all others remain constant).

8. How is a reactor protected against burnout?

NUCLEAR TECHNOLOGY

MODULE 4-9 REACTOR HEAT TRANSFER LIMITS



HEAT TRANSFER AND FLUID FLOW

COURSE 4

TERC-SW

TECHNICAL EDUCATION RESEARCH CENTER — SOUTHWEST
4201 LAKE SHORE DRIVE WACO, TEXAS

COURSE MODULES

COURSE 4 HEAT TRANSFER AND FLUID FLOW

MODULE 4-1 Basic Properties of Fluids

MODULE 4-2 Fluid Statics

MODULE 4-3 Fluid Dynamics

MODULE 4-4 Heat Transfer by Conduction

MODULE 4-5 Heat Transfer by Convection

MODULE 4-6 Heat Transfer by Radiation

MODULE 4-7 Change of Phase - Boiling

MODULE 4-8 Burnout and Flow Instability

MODULE 4-9 Reactor Heat Transfer Limits

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INTRODUCTION

Theoretically, nuclear reactor heat generation rate is not physically limited; in fact, there is no theoretical upper limit to reactor power output. Therefore reactor design must consider such factors as rate of heat transfer (heat flux), nucleate boiling ratio, fuel surface temperature and power distribution.

In this module, these factors are considered as they apply to reactor heat transfer limitations.

MODULE PREREQUISITES

The student should have completed all prior modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe variables that determine axial power distribution, and give a typical value for the axial peaking factor.

2. Describe variables that determine radial power distribution, and give a typical value for radial peaking factor.
3. List peaking and hot channel factors that cause heat generation and heat transfer rates to differ from nominal.
4. Explain how maximal heat flux is determined (in terms of peaking factors).
5. Define peak heat flux limit and explain determining factors.
6. Express typical values for heat flux, maximum fuel surface temperature and maximum fuel centerline temperature for PWR's and BWR's.
7. Explain why uniform power distribution is desirable.

HEAT TRANSFER WITHIN REACTOR FUEL

When a reactor fuel rod is designed, one limiting design consideration is preventing of fuel melting. If reactor fuel melts, undesirable events occur, such as the release of fission product gases, which cause high internal fuel rod pressures. Therefore, it is desirable to limit reactor operation to prevent fuel melting.

Fuel cladding temperature is directly related to reactor coolant pressure, flow rate, and bulk coolant temperature. Understanding the limit on fuel surface temperature is prerequisite to understanding the relationship of cladding temperature to centerline fuel temperature.

UO_2 (fuel material) has a melting point of about 5000°F. UO_2, in ceramic form, a good insulating material in itself, has a high resistance to heat flow, (Figure 4-9-1). And heat transfer calls for increasing fuel temperature as power (heat) increases. As power increases, centerline fuel temperature approaches the melting point (Figure 4-9-2). The value of ∿6 kW/ft is an average specific power level, typical for a power reactor. A maximum of 19 kW/ft is a typical maximum specific power level, approaching centerline fuel melting. Temperature drop, from center of fuel to edge of fuel pellet (for average power generation rate), is approximately 800°F. Between fuel pellet surface and cladding, fission gases have a high resistance to heat flow, thus an additional 100°F temperature drop is encountered. Heat conductance through the fuel cladding is very good - only a small temperature drop is observed. At a higher specific power level, centerline fuel temperature approaches melting point at the same cladding surface temperature.

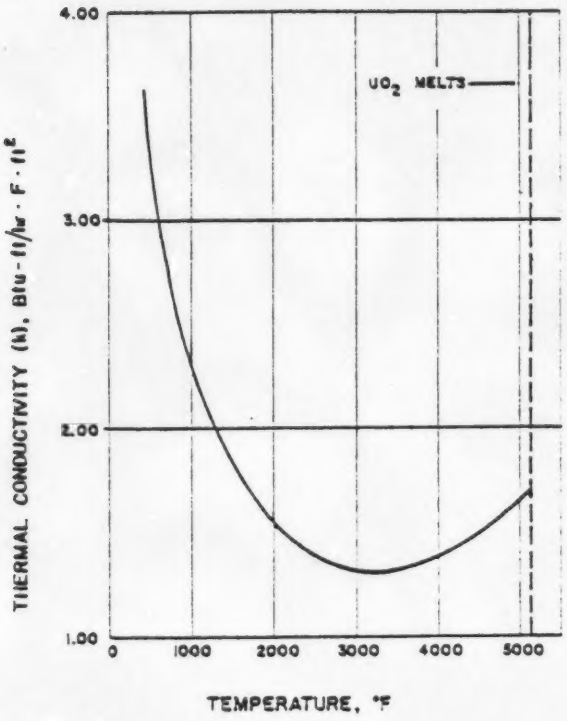

Figure 4-9-1.
Thermal conductivity for UO_2.

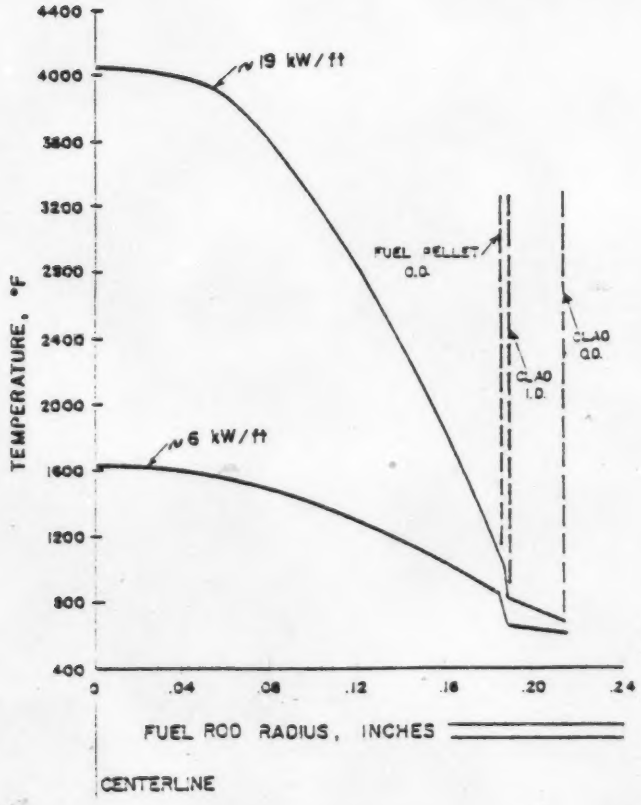

Figure 4-9-2.
Internal fuel temperature UO_2.

POWER AND SPECIFIC POWER

A reactor license specifies the maximum thermal power level to be generated in the fuel. Typical power ratings of reactors under construction are as high as 3800 MW thermal (+).

EXAMPLE

Given: A 3800-MW thermal reactor with 200 fuel assemblies; each assembly contains 231 fuel rods and 25 vacant locations for control components and instrumentation; each rod is 12 feet long.

Find: Specific power in kW/ft.

Solution:

$$\text{kW/ft} = \frac{3800\ \text{MW} \times 100\ \text{kWt/MWt}}{200\ \text{fuel assemblies} \times \frac{231\ \text{fuel rods}}{\text{fuel assembly}} \times \frac{12\ \text{feet}}{\text{fuel rods}}}$$

$$= 6.85\ \text{kW/ft}.$$

Equation 4-9-1
(Equation = Eq.)

AVERAGE SPECIFIC POWER AND MAXIMUM SPECIFIC POWER

Power generation in a reactor core is non-uniform. The power calculated in the preceding section is only an average theoretical value for a given reactor configuration. A ratio between maximum specific power and average specific power is a unitless ratio of peak-to-average values, called "gross peaking factor, F_Q."

$$F_Q = \frac{\text{peak power}}{\text{average power}}.$$

By using the average from the previous example,

$$F_Q = \frac{19 \text{ kW/ft}}{6.88 \text{ kW/ft}}$$

$$= 2.77.$$

GROSS PEAKING FACTOR

Gross peaking factor includes nuclear peaking factor and a mechanical peaking factor. The nuclear peaking factor takes into consideration a radial peaking factor, as well as axial peaking (Figure 4-9-3). The nuclear flux shape in a

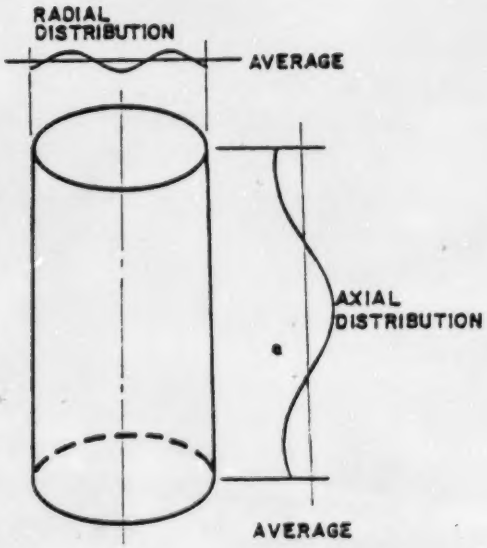

Figure 4-9-3.
Radial and axial reactor power (and neutron flux) distribution.

reactor is ideally a cosine shape, with a peak-to-average ratio of about 1.5. This ratio applies when the reactor is operated with control rods fully withdrawn, and when the general shape is due to the concentration of fission in the center of the core.

The radial peaking factor is somewhat lower. It shows the effects of loading fuel and control components in the reactor to suppress center peaks and thereby, reduce the peaking factor. Radial peaking factors of 1.33 or less, which are reasonable design goals, can be achieved easily in practical operation.

In addition to nuclear peaking factors, mechanical peaking factors also must be considered:

Fuel pellet fabrication tolerances.
Fuel assembly tolerances.
Hot channel factors.
Fuel bundle-to-bundle variations.

Fuel Pellet Fabrication Tolerances

Enrichment tolerance, with typical limits: $\pm$ 0.013% (weight % of ^{235}U) with average values of 2 to 3%.

Pellet density tolerance, with typical limits: $\pm$ 1.5% of theoretical density.

Pellet diameter tolerance: $\pm$ 0.0005 inch (with typical values of 0.333 inch).

Stack length tolerance: $\pm$ 0.75 inch (with typical values of 144 inch).

Fuel Assembly Tolerances

Fuel rod pitch (center-to-center spacing) tolerance: $\pm$ 0.022 inch (with typical values of 0.500 inch).

Fuel rod diameter tolerance: $\pm$ 0.002 inch.

Hot Channel (Peak-to-Average) Factors

Local surface heat flux values: 1.015.

Average rod power values: 1.011.

Flow area reduction factor: 0.98.

Fuel Bundle-to-Bundle Variation

Proximity to neighboring fuel bundles assumes that the closest proximity occurs at the hot channel, effecting flow areas and local peaking distribution.

If total effects of mechanical peaking factors are typically below the range of 1.30, the gross peaking factor of 2.77 in the previous example is fairly close, even when all considerations are included.

EXAMPLE

Given: Axial peaking (F_{PA} = 1.5); radial peaking (F_{PR} = 1.33); mechanical peaking (F_M = 1.3).

Find: Gross peaking (F_Q).

Solution: $F_Q = F_{PA} \times F_{PR} \times F_M$ Eq. 4-9-2

$= 1.5 \times 1.33 \times 1.3$

$= 2.59$

HOT CHANNEL FACTORS

In a reactor core, with unequal flux and unequal power distribution, one fuel element will have a larger output than any other. By assuming the worst combination of power and flow and power distribution in one fuel element, a comparison of peak-to-average may be stated as follows:

$$F_R = \frac{\text{Maximum power from any fuel assembly}}{\text{Average power from all fuel assemblies}}$$

where

F_R = radial peaking factor.

Along the length of a fuel assembly, one place will produce a higher power output than any other place. Its peak-to-average ratio is stated as follows:

$$F_A = \frac{\text{Maximum specific power (kW/ft)}}{\text{Average specific power (kW/ft)}}$$

where

F_A = axial peaking factor.

Within a fuel assembly, one fuel rod will produce more power than any other. Its peak-to-average ratio is stated as follows:

$$F_M = \frac{\text{Maximum power from any fuel rod}}{\text{Average power from all fuel rods}}$$

where

F_M = mechanical peaking factor.

Although it is highly unlikely that all of these conditions will occur simultaneously in one fuel assembly, at one given level, and in one fuel rod, it is theoretically possible. The total factor (radial peaking factor x axial peaking factor x local peaking factor) is called the "hot channel factor."

EXAMPLE

Given: A reactor rated at 3800 MWt, which has 200 fuel assemblies, each with 231 fuel rods 12 feet long. Radial peaking factor (F_Q = 1.33); axial peaking factor (F_{PA} = 1.50); local (mechanical) peaking factor (F_M = 1.15).

Find: 1) Power output of hottest fuel assembly. 2) Power output of hottest rod in hottest assembly. 3) Highest specific power output from the hottest rod.

Solution:

1) $= \frac{3800 \text{ MWt}}{200 \text{ fuel assemblies}} \times 1.33$

$= 19 \text{ MWt} \times 1.33$

$= 25.27 \text{ MWt}$

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2) $= \frac{25.27 \text{ MWt}}{231 \text{ rods}} \times 1.15$

$= 0.1094 \text{ MWt} \times 1.15$

$= 0.1258 \text{ MWt}$

3) $= \frac{0.1258 \text{ MWt}}{12 \text{ feet}} \times 1.50$

$= 0.00148 \text{ MWt/feet} \times 1.50$

$= 0.015728 \text{ MWt/feet}$

$= 15.73 \text{ kWt/feet.}$

EXERCISES

1. What is limiting factor on reactor power output?
2. What are limiting factors on reactor fuel temperature?
3. Why is this limit imposed?
4. Describe radial, axial, and local (mechanical) peaking factors.
5. For a reactor of 3800 MWt, determine critical heat flux if minimum DNBR is 1.55 and there are 215 fuel assemblies of 231 fuel rods each. (Each fuel rod is 0.375 inch in diameter and 12 feet long. Radial peak = 1.27; axial peak = 1.50; local peak = 1.12.

MATERIALS

None.

PROCEDURES

Obtain a copy of nuclear plant operating parameters; determine actual flux distribution and peaking factors.

DATA TABLE

None.

REFERENCE MATERIALS

Eckert, E.R.G. and Drake, R.M., Jr. Analysis of Heat and Mass Transfer. New York: McGraw-Hill, 1973.

Given: Example on page 10 of this module. If $F_Q = 1.36$, and all other parameters remain as given, find the three variables.

NUCLEAR TECHNOLOGY

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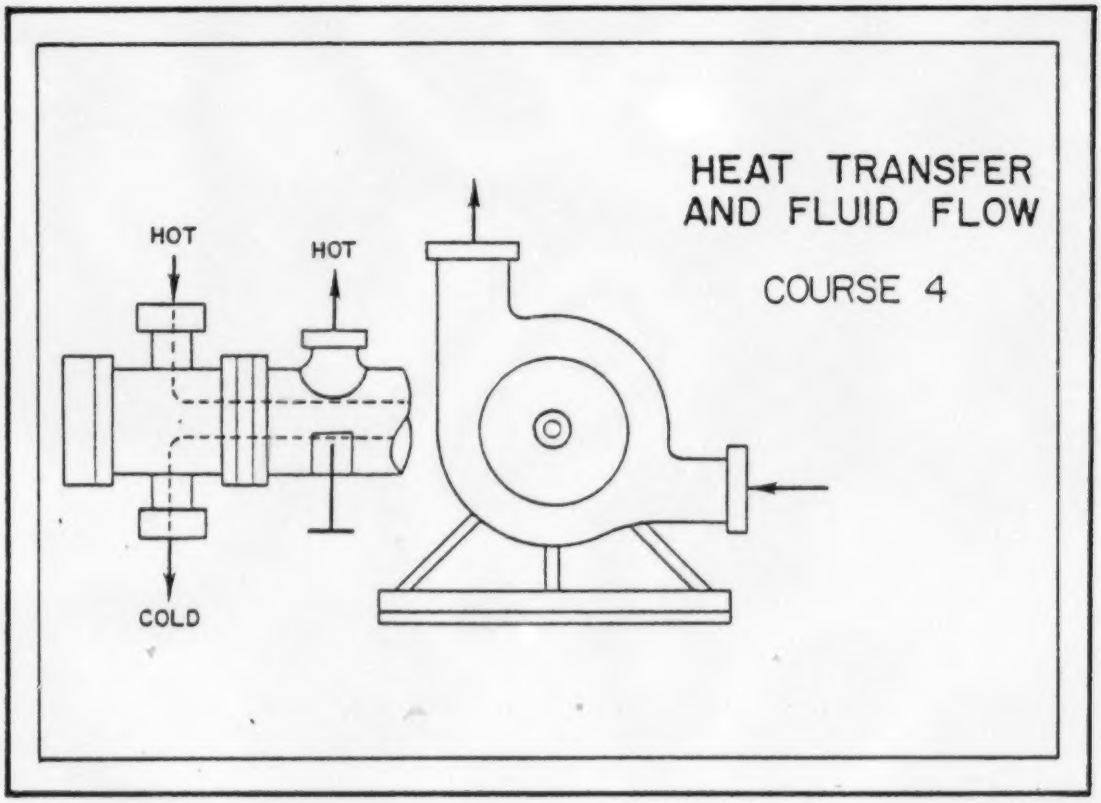
COURSE 4 - HEAT TRANSFER AND FLUID FLOW



TERC-SW 216

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NUCLEAR TECHNOLOGY SERIES

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for

COURSE 4, HEAT TRANSFER AND FLUID FLOW (NINE MODULES)

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